EXPERIMENTAL VERIFICATION OF THE KEEY-SUZUKI CHARACTERISTIC DRYING CURVE EQUATIONS FOR POROUS, NON-HYGROSCOPIC MATERIAL.

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Ter Leong Yong
University of Canterbury

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CONTENT

1. ABSTRACT

The characteristic drying curve theory for the drying of spherical particles developed by Keey and Suzuki (2) was verified by drying 10 mm diameter brick particles in a bench-size rotary dryer.

The drying was in the slow regime ($\mathcal{N}_{cr}<2$).

The experimental results appear to support the theory.

Thus, it is considered that the characteristic drying curve theory for the drying of a slab of infinite extent developed by the same authors (1) will hold.

2. INTRODUCTION

2.1 Background

The characteristic drying curve concept is useful in the process design of drying equipment. The characteristic drying curve equation in its general form, $f = f\ (\Phi)^n$, has one disadvantage in that one has to do tedious laboratory tests before the characteristic drying curve of a material can be obtained.

2.2 The Characteristic Drying Curve

A more rigorous treatment of the characteristic drying curve theory was proposed by Keey and Suzuki (1) based on the drying of a porous, non-hygroscopic slab of infinite extent, later extended to the drying of spherical particles (2).

The characteristic drying equations express the characteristic moisture content, Φ, as a non-explicit function of the relative drying flux, f,

$$\Phi = f\{1 - (1-f)/f\gamma Bi\}^2 \qquad (2.1)$$

for $\mathcal{N}_{cr} < 2$,

$$\Phi = \frac{1 - (1-f)/f\gamma Bi - 2/3\,\mathcal{N}f}{1 - 2/3\mathcal{N}} \qquad (2.2)$$

for $\mathcal{N}_{cr} > 2,\ \delta < 1$,

$$\Phi = \frac{\mathcal{N}f\ \{1 - (1-f)/f\gamma Bi\}^2}{3\ (1-2/3\mathcal{N})} \qquad (2.3)$$

for $\mathcal{N}_{cr} > 2, \delta > 1$.

In the above expressions,

Φ - Characteristic moisture content

f - Relative drying flux

γ - Evaporative Coefficient (a property of the drying material)

Bi - Biot number

$\mathcal{N}$ - Intensity of Drying (defined later in this chapter).

The characteristic moisture content can be expressed in terms of the moisture content (dry basis) as follows:-

$$\Phi = \frac{X - X^*}{X_{cr} - X^*} \tag{2.4}$$

In equation (2.4), X is the moisture content, X^* is the equilibrium moisture content, and X_{cr} is the critical moisture content. For a non-hygroscopic material, X^* is zero.

Under intensive drying conditions the characteristic drying curve is a function of the relative intensity of drying whereas under less intensive drying it is not. Drying is said to be intensive if $\mathcal{N}$ is greater than 2 at the critical point, (Appendix, reference 1), when a drying front will appear. The intensity of drying $\mathcal{N}$, is defined by Keey and Suzuki to be,

$$\mathcal{N} = \frac{N_a{}^{o}b}{D_a X_o \rho_s} \tag{2.5}$$

Where N_a^o - initial (unhindered) drying flux,

b - thickness of material

D_a - constant apparent diffusivity,

ρ_s - density of material,

X_o - moisture content (dry basis).

The intensity of drying decreases along the dryer from the air inlet under changing external drying conditions.

The characteristic drying equations for the drying of porous, non-hygroscopic spherical particles are :-

$$\Phi = fE^2 \tag{2.6}$$

for $\mathcal{N}' < 2$,

$$\Phi = \frac{\mathcal{N}'^4}{5\mathcal{N}'^3 - 10\mathcal{N}'^2 + 10\mathcal{N}' - 4} .f.\, E^2 \tag{2.7}$$

for $2 < \mathcal{N}' < \frac{2E}{f}$,

$$\Phi = \frac{1 - \frac{2E}{\mathcal{N}' f} + \frac{2E^2}{\mathcal{N}'^2 f^2} - \frac{4E^3}{5\mathcal{N}'^3 f^3}}{1 - \frac{2}{\mathcal{N}'} + \frac{2}{\mathcal{N}'^2} - \frac{4}{5\mathcal{N}'^3}}\; E^3 \tag{2.8}$$

for $\mathcal{N}' > \frac{2E}{f}$.

$\gamma Bi \to \infty$

$$\text{Where} \quad E = 1 - \frac{\xi}{R} = \frac{f\,\gamma Bi}{1-f-f\gamma Bi} \tag{2.9}$$

$E \to \frac{f\gamma Bi}{1-f\gamma Bi}$

$$\text{and } \mathcal{N}' = \frac{\dot{N}_a^o R}{D_d X_o \rho_s} \tag{2.10}$$

In equation (2.10) R is the radius of the sphere.

2.3 Objective

The aim of this project is to verify the theoretical characteristic drying curve experimentally. In the drying experiment, red brick particles of approximately 10 mm diameter were dried in a bench scale rotary dryer, under changing external conditions. The theoretical characteristic drying curve verified is evaluated using experimental values of γBi, $\mathcal{N}^o$, Y_w, Y_{GO}, $^L/G$, etc.

The method involves simple algebraic manipulation to transform the non-explicit characteristic drying curve equations into polynomials in f. From there, they can easily be solved by Newton - Raphson (4) iterative method of solving linear equations. Newton - Raphson iterative method is easily adaptable to machine computation.

The author has written computer programs (see Fig. 1a-f) to solve the characteristic drying equations for the Burroughs B6700 Computer. A flow chart is shown in Fig. 1.

Theoretical drying-rate profiles, see Appendices 7.9, merely for academic interest, were evaluated for the following drying schedules:-

1. co-current, adiabatic flow,
2. counter current, adiabatic flow,
3. co-current, isothermal flow,

and 4. counter-current, isothermal flow,

for the drying of a porous, non-hygroscopic slab of infinite extent and cases 1 and 2 for drying of spherical particles.

Drying under adiabatic conditions is more common in industry, but isothermal drying is encountered too. Under adiabatic drying, no heat is added or removed from the dryer, therefore, the air temperature drops as the gas humidifies. Humidification thus follows the adiabatic Saturation curve for a constant wet-bulb temperature.

On the other hand, heat is constantly added to the humidifying gas to maintain a constant temperature in isothermal drying. The humidification follows the isothermal line, thus, the wet bulb temperature increases as the gas humidifies. The shift in wet-bulb saturation humidity of the gas can be expressed as,

$$\frac{\Delta Y_W}{\Delta Y_G} = A \qquad (2.11)$$

In obtaining equation (2.11) we have to assume that the slopes of the adiabatic saturation curve and moisture saturation curve to be almost constant. This assumption holds quite well if the external conditions do not change greatly. ΔY_W in equation (2.11) is the change in saturation humidity at the wet-bulb temperature, Y_W: ΔY_G is the change in bulk air humidity, Y_G and A is a constant.

3.0 NUMERICAL ANALYSIS

3.1 Newton-Raphson Method

From the definition of the intensity of drying, expression (2.5),

$$\mathcal{N} = \frac{N_a^{o} b}{\rho_s X_o D_a} \qquad (2.5)$$

if N_a^{o} is taken as the initial (unhindered) drying flux at the solid inlet to the adiabatic co-flow dryer, then

$$\mathcal{N}^{o} = \frac{N_a^{o} b}{\rho_s X_o D_a} \qquad (3.1)$$

For drying under changing external drying conditions, we can say,

$$\mathcal{N} = \frac{N_a b}{\rho_s X_o D_a} \qquad (3.2)$$

Where N_a is now the varying local drying flux.

Expressions (3.1) and (3.2) give,

$$\frac{\mathcal{N}}{\mathcal{N}^{o}} = \frac{N_a}{N_a^{o}} \qquad (3.3)$$

therefore,

$$\mathcal{N} = \frac{N_a}{N_a^{o}} \mathcal{N}^{o} \qquad (3.4)$$

$$= f \frac{(Y_W - Y_G)}{Y_W - Y_{GO}} \mathcal{N}^{o} \qquad (3.5)$$

$$= cf \qquad (3.6)$$

Where $C = \dfrac{(Y_W - Y_G)}{(Y_W - Y_{GO})}$ (3.7)

In equation (3.5), Y_W is wet-bulb saturation humidity, Y_{GO} is the bulk air humidity at solid inlet and Y_G is the bulk air humidity.

Substituting expression (3.6) into expression (~~3~~2.2) becomes,

$$\Phi = \frac{1 - (1-f)/f\gamma Bi - 2/3cf^2}{1 - 2/3cf} \qquad (3.8)$$

Manipulating expression (3.8) algebraically gives a quadratic equation in f,

$$g(f) = (\Phi - \frac{1}{\gamma Bi} - 1)f^2 + (\frac{1}{\gamma Bi} - \frac{2\Phi}{3c})f + \frac{2}{3c} = 0 \qquad (3.9)$$

Newton-Raphson method therefore iteratively finds the zero of the function g(f).

From equation (3.9) if we put,

$$g(f) = (\Phi - \frac{1}{\gamma Bi} - 1)f^2 + (\frac{1}{\gamma Bi} - \frac{2\Phi}{3c})f + \frac{2}{3c} \qquad (3.10)$$

$$\therefore \frac{d}{df}(g(f)) = 2(\Phi - \frac{1}{\gamma Bi} - 1)f + (\frac{1}{\gamma Bi} - \frac{2\Phi}{3c})$$

Expressions (3.10) can be solved iteratively conveying to a solution of accuracy ±0.0001 in about 4 iterations.

Similarly we can put expression (2.1) as,

$$g(f) = \{(\gamma Bi)^2 + 2\gamma Bi + 1\}f^2 - \{2\gamma Bi + (\gamma Bi)^2\Phi + 2\}f + 1 \qquad (3.11)$$

$$\frac{d}{df}g(f) = 2\{(\gamma Bi)^2 + 2\gamma Bi + 1\}f - \{2\gamma Bi + (\gamma Bi)^2\Phi + 2\}$$

Expression (2.3) as a cubic in f,

$$g(f) = \{1 + \frac{2}{\gamma Bi} + \frac{1}{(\gamma Bi)^2}\}f^3 - \{\frac{2}{\gamma Bi} + \frac{2}{(\gamma Bi)^2}\}f^2 + \{\frac{1}{(\gamma Bi)^2} - \frac{3\Phi}{C}\}f + \frac{2\Phi}{C^2} \qquad (3.12)$$

$$\frac{d}{df}(g(f)) = 3(1 + \frac{2}{\gamma Bi} + \frac{1}{(\gamma Bi)^2})f^2 - 2(\frac{2}{\gamma Bi} + \frac{2}{(\gamma Bi)^2})f + (\frac{1}{(\gamma Bi)^2} - \frac{3\Phi}{C})$$

Given similar consideration from expressions (2.5), (2.6) and (2.7) for drying of non-hygroscopic spherical particles respectively becomes

$$g(f) = fE^2 - \Phi$$

$$\frac{d}{df}(g(f)) = f.2E\frac{dE}{df} + E^2 \qquad (3.13)$$

$$g(f) = \frac{C^4 E^2 f^5}{5c^3f^3 - 10c^2f^2 + 10cf - 4} - \Phi$$

$$(3.14)$$

$$\frac{d}{df}(g(f)) = \frac{U(2E\mathcal{N}'^4 f\frac{dE}{df} + 5E^2\mathcal{N}'^4) - E^2\mathcal{N}'^5(15\mathcal{N}'^2 - 20\mathcal{N}' + 10)}{U^2}$$

$$g(f) = \frac{E^3V}{W} - \Phi$$

$$\frac{d}{df}(g(f)) = (W(3E^2\frac{dE}{df} - \frac{8\mathcal{N}' fE^3\frac{dE}{df} - 4\mathcal{N}' E^4}{\mathcal{N}'^2 f^2} + \frac{10\mathcal{N}'^2 f^2E^4\frac{dE}{df} - 8\mathcal{N}'^2 fE^5}{\mathcal{N}'^4 f^4} \qquad (3.15)$$

$$- \frac{120\mathcal{N}'^3 f^3E^5\frac{dE}{df} - 120\mathcal{N}'^3 f^2E^6}{25\mathcal{N}'^6 f^6}) - E^3\,V(\frac{2}{\mathcal{N}' f} - \frac{4}{\mathcal{N}'^2 f} + \frac{12}{5\mathcal{N}'^3 f}))$$

Where $U = 5\mathcal{N}'^3 - 10\mathcal{N}'^2 + 10\mathcal{N}' - 4$ (3.16)

$$V = 1 - \frac{2E}{\mathcal{N}'f} + \frac{2E^2}{\mathcal{N}'^2 f^2} - \frac{4E^3}{5\mathcal{N}'^3 f^3} \qquad (3.17)$$

and $$W = 1 - \frac{2}{\mathcal{N}'} + \frac{2}{\mathcal{N}'^2} - \frac{4}{5\mathcal{N}'^3} \qquad (3.18)$$

The numerical analysis is carried out in steps of decreasing characteristic moisture content, Φ. At Φ equal to unity, the intensity of drying was evaluated from equation (3.6), putting f=1. If $\mathcal{N}'$ evaluated at the critical point is greater than 2, the relative drying flux f is evaluated using expressions (3.10), for the drying of a slab of infinite extent. However, since expressions (3.10) is invalid when the drying front has swept through the material, that is $\delta > 1$. It was therefore necessary to obtain an expression in terms of f to check the validity of expressions (3.10) in the evaluation for the condition when the profile characteristic of low-intensity drying begins.

From equation (51), reference 1, we obtain,

$$\delta - \xi = 2/\mathcal{N}f \qquad (3.19)$$

Where δ = fractional penetration of drying front

and ξ = fractional depth of recession of evaporative interface.

Equation (3.19) then becomes,

$$\delta = \xi + 2/\mathcal{N}f \qquad (3.20)$$

Substituting equation 43, reference 1, for ξ in equation 3.20 we get,

$$\delta = (1-f)/f\gamma Bi + 2/\mathcal{N}f \qquad (3.21)$$

For $\delta < 1$, i.e. validity of expression (3.10), we must have,

$$\frac{(1-f)}{f\gamma Bi} + \frac{2}{\mathcal{N}f} < 1 \qquad (3.22)$$

Solving for f, we get,

$$f > \frac{\left(\frac{1}{\gamma Bi} + \frac{2}{\mathcal{N}}\right)}{1+\frac{1}{\gamma Bi}} \qquad (3.23)$$

for high intensity drying to prevail.

If expression (3.23) is not satisfied, then we evaluate the relative drying flux, f using expressions (3.12).

3.2 Sample Calculation - adiabatic, co-current drying.

Data

$Y_W = 0.0371$
$Y_{GO} = 0.0077$
$\mathcal{N}^o = 10$
$X_o = 1.5$
$X_z = 0.2$
$\gamma Bi = 10$
$X_{cr} = 1.0$
$X^* = 0.0$
$G/L = 100$

a. Mass Balance

$$L(X_o - X_{cr}) = G(Y_G - Y_{GO})$$

$$Y_G = \frac{(X_o - X_{cr})}{100} + Y_{GO}$$

$$= 0.0127$$

b. Intensity of drying at the critical point, using expression (3.6), that is,

$$\mathcal{N} = cf \qquad (3.6)$$

at critical point f = 1,

$$\therefore \mathcal{N} = c$$

$$= \frac{(Y_W - Y_G)}{Y_W - Y_{GO}} \cdot \mathcal{N}^o$$

$$= \frac{0.0371 - 0.0127}{0.0371 - 0.0077} \cdot 10$$

$$= \underline{8.3} \ (>2)$$

$\therefore$ Evaluate the relative drying flux using expression (3.10).

c. Newton-Raphson Iteration

$\Phi = 0.9$, guess $f = 0.7$

Results:

f old	g	$\frac{dg}{df}$	$g/\frac{dg}{df}$	f new
0.07000	+0.00172	-0.2523	-0.00682	0.7068
0.7068	-0.000006	-0.2550	-0.000024	0.7068
			(<0.0001)	

$\therefore$ answer is $f = 0.7068$, $\Phi = 0.9$.

d. Check criterion for the validity of expression (3.10)

$\Phi = 0.9$ $f = 0.7068$, $\mathcal{N} = cf = 5.8664$

Expression (3.23)

$$f > \frac{\frac{1}{\gamma Bi} + \frac{2}{\mathcal{N}}}{1 + \frac{1}{\gamma Bi}}$$

$$= \frac{0.1 + \frac{2}{5.8664}}{1 + 0.1}$$

$$= 0.4008$$

Since $f = 0.7068$ (>0.4008), expression 3.10 was valid in the evaluation. The results are summarised in Tabulation 1.

Tabulation 1

Results of Sample Calculation

Φ	Y_G	C	f	$\mathcal{N}$	$f(Y_W - Y_G)$
1.5	0.0077	10	1.0000	10	0.0294
1.4	0.0087	9.66	1.0000	9.66	0.0284
1.3	0.0097	9.32	1.0000	9.32	0.0274
1.2	0.0107	8.98	1.0000	8.98	0.0264
1.1	0.0117	8.64	1.0000	8.64	0.0254
1.0	0.0127	8.30	1.0000	8.30	0.0244
0.9	0.0137	7.96	0.7068	5.8664	0.0167
0.8	0.0147	7.62	0.5924	4.514	0.0133
0.7	0.0157	7.28	0.5355	3.898	0.0115
0.6	0.0167	6.94	0.5079	3.424	0.0104
0.5	0.0177	6.60	0.4756	3.139	0.0092
0.4	0.0187	6.26	0.4371	2.736	0.0080
0.3	0.0197	5.92	0.3898	2.308	0.0068
0.2	0.0207	5.58	0.3288	1.835	0.0054

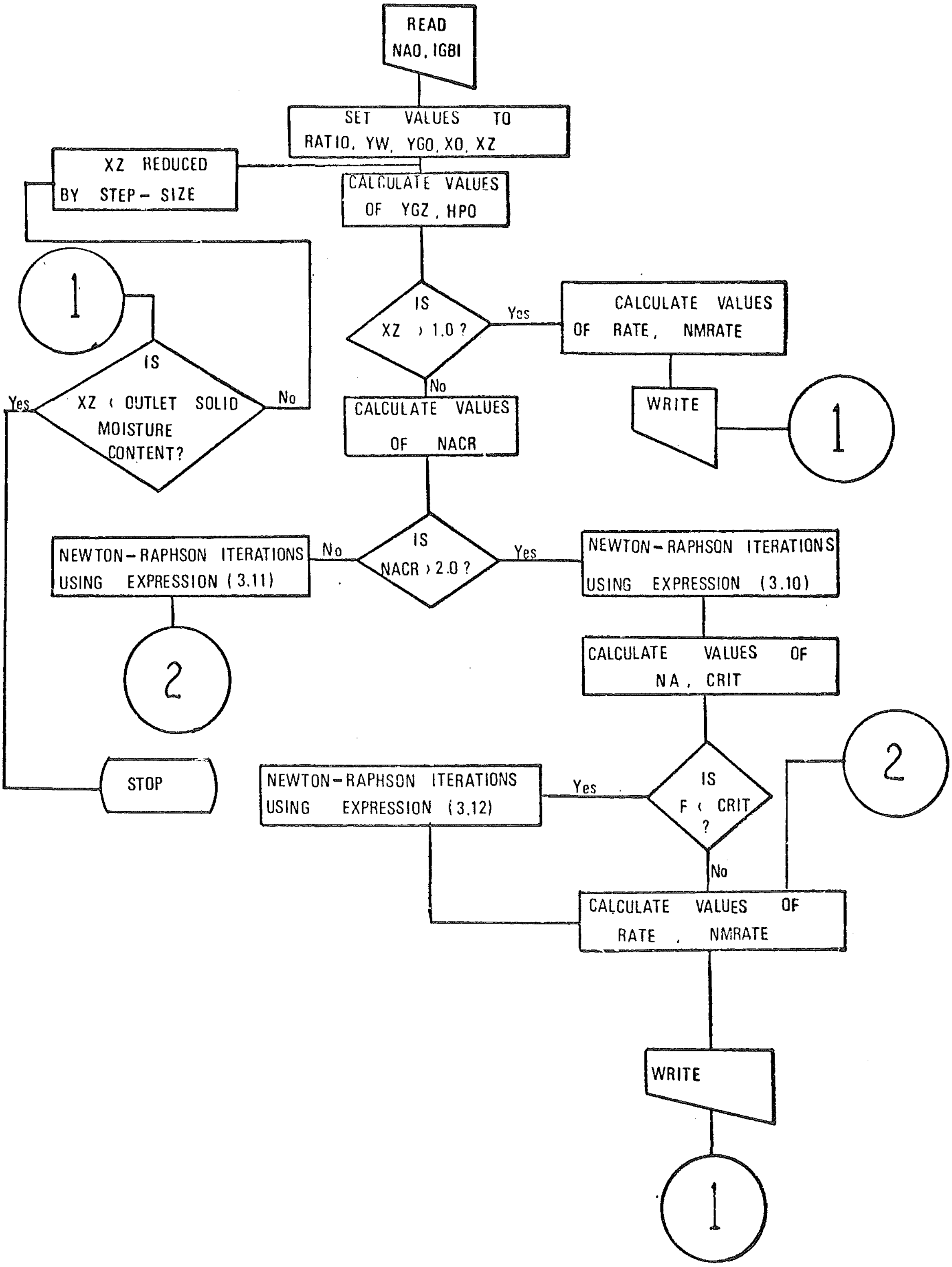

Fig 1. Computer flow diagram for evaluating drying rate profile for a non-hygroscopic material of infinite extent.

COMPUTER PRINTOUTS

1. Cocurrent, adiabatic, drying of slab of infinite extent.
2. Counter-current, adiabatic, drying of slab of infinite extent.
3. Cocurrent, isothermal, drying of slab of infinite extent.
4. Counter-current, isothermal, drying of slab of infinite extent.
5. Cocurrent, adiabatic, drying of spherical particles.
6. Counter-current, adiabatic, drying of spherical particles.

each program consists of two pages.

```
C     COCURRENT DRYER******NTU=1.5                                  C  000:0000:5
                                                                     START OF SEGMENT 002
      REAL NMRATE,NAO,NA,NACR,NACON                                 C  002:0000:0
   25 READ(5,10,END=222)NAO,IGBI                                    C  002:0000:0
                                                                          FIB IS 0006 LONG
   10 FORMAT(F7.4,I2)                                               C  002:000A:0
      I=0                                                           C  002:000A:0
      J=0                                                           C  002:000A:4
      RATIO=100.                                                    C  002:000B:2
      YW=.0371                                                      C  002:000C:1
      YGO=.0077                                                     C  002:000E:3
      XO=1.5                                                        C  002:0010:3
      XZ=1.5                                                        C  002:0012:3
   22 YGZ=(XO-XZ)/RATIO+YGO                                         C  002:0014:3
      HPO=YW-YGZ                                                    C  002:0016:5
      IF(XZ.LT..995)GO TO 20                                        C  002:0018:1
      IF(XZ.GT.1.005)GO TO 92                                       C  002:001A:4
      NACR=HPO/.0294*NAO                                            C  002:001D:4
   92 F=1.                                                          C  002:0021:1
      RATE=1.*HPO                                                   C  002:0021:5
      TIP=1./RATE                                                   C  002:0023:0
      NMRATE=RATE/.0294                                             C  002:0024:1
      GO TO 40                                                      C  002:0026:4
   20 NACON=HPO/.0294*NAO                                           C  002:0027:1
      IF(J.EQ.1)GO TO 30                                            C  002:002A:1
      IF(I.EQ.1)GO TO 88                                            C  002:002B:2
      IF(NACR.LT.2.)GO TO 50                                        C  002:002C:3
      I=1                                                           C  002:002D:5
      F=.7                                                          C  002:002E:3
   88 A56=XZ-1./IGBI-1.                                             C  002:0030:3
      B56=1./IGBI-2.*XZ/(3.*NACON)                                  C  002:0032:3
      C56=2./(3.*NACON)                                             C  002:0035:4
      DO 11 K=1,10                                                  C  002:0037:3
      G=A56*F*F+B56*F+C56                                           C  002:0039:0
      GDIFF=2.*A56*F+B56                                            C  002:003C:2
      FSFNEW=G/GDIFF                                                C  002:003E:4
      IF(ABS(FSFNEW).LT..0001)GO TO 12                              C  002:0040:0
      FNEW=F-FSFNEW                                                 C  002:0042:4
   11 F=FNEW                                                        C  002:0044:0
      GO TO 3                                                       C  002:0047:0
   12 NA=NACON*F                                                    C  002:0047:3
      CRIT=(1./IGBI+2./NA)/(1.+1./IGBI)                             C  002:004B:5
      IF(F.GT.CRIT)GO TO 100                                        C  002:004C:1
      J=1                                                           C  002:004D:3
   30 A64=1.+2./IGBI+1./(IGBI*IGBI)                                 C  002:004E:1
      B64=2./IGBI+2./(IGBI*IGBI)                                    C  002:0051:0
      C64=1./(IGBI*IGBI)-3.*XZ/NACON                                C  002:0053:4
      D64=2.*XZ/(NACON*NACON)                                       C  002:0056:4
      DO 111 K=1,10                                                 C  002:0058:5
      G=A64*F*F*F-B64*F*F+C64*F+D64                                 C  002:005A:0
      GDIFF=3.*A64*F*F-2.*B64*F+C64                                 C  002:005F:2
      FSFNEW=G/GDIFF                                                C  002:0063:4
      IF(ABS(FSFNEW).LT..0001)GO TO 100                             C  002:0065:0
      FNEW=F-FSFNEW                                                 C  002:0067:4
  111 F=FNEW                                                        C  002:0069:0
      GO TO 3                                                       C  002:006C:0
   50 A44=IGBI*IGBI+2.*IGBI+1.                                      C  002:006C:3
      B44=2.*IGBI+XZ*IGBI*IGBI+2.                                   C  002:006F:0
      DO 211 K=1,10                                                 C  002:0072:2
      G=A44*F*F-B44*F+1.                                            C  002:0073:0
      GDIFF=2.*A44*F-B44                                            C  002:0076:1
      FSFNEW=G/GDIFF                                                C  002:0078:3
      IF(ABS(FSFNEW).LT..0001)GO TO 100                             C  002:0079:5
      FNEW=F-FSFNEW                                                 C  002:007C:4
  211 F=FNEW                                                        C  002:007E:0
      GO TO 3                                                       C  002:0081:0
  100 RATE=F*HPO                                                    C  002:0081:3
      NMRATE=RATE/.0294                                             C  002:0082:5
      TIP=1./RATE                                                   C  002:0084:4
   40 WRITE(6,33)XZ,F,RATE,NMRATE,NACR,NACON,RATIO,TIP              C  002:0085:5
                                                                          FIB IS 0006 LONG
   33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F6.4   C  002:0097:2
     1,5X,F9.4)                                                     C  002:0097:2
      IF(J.EQ.1)WRITE(6,522)                                        C  002:0097:2
      CONTINUE                                                      C  002:009C:2
```

```
      IF(XZ.LE..2)GO TO 25                                            C  002:009C:2
      XZ=XZ-.1                                                        C  002:009E:4
      GO TO 22                                                        C  002:00A1:4
    3 WRITE(6,200)XZ                                                  C  002:00A2:1
  200 FORMAT(1X,'XZ=',F4.2,10X,'NO CONVERGENCE')                      C  002:00A9:2
      IF(J.EQ.1)WRITE(6,522)                                          C  002:00A9:2
  522 FORMAT(95X,'FRONT DISAPPEARED')                                 C  002:00AE:2
      GO TO 25                                                        C  002:00AE:2
  222 STOP                                                            C  002:00AE:5
      END                                                             C  002:00AF:4
      002:00B3:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0000
                                                                   SEGMENT 002 IS 00C2 LONG
```

```
C       COUNTERCURRENT DRYER****************                            C  002:0000:5
                                                                          START OF SEGMENT 002
        REAL NMRATE,NAO,NA,NACR,NACON                                   C  002:0000:0
     25 READ(5,10,END=222)NAO,IGBI                                      C  002:0000:0
                                                                              FIB IS 0006 LONG
     10 FORMAT(F7.4,I2)                                                 C  002:000A:0
        I=0                                                             C  002:000A:0
        J=0                                                             C  002:000A:4
        RATIO=100.                                                      C  002:000B:2
        YW=.0371                                                        C  002:000C:1
        YGZ=.0077                                                       C  002:000E:3
        XO=1.5                                                          C  002:0010:3
        XZ=.2                                                           C  002:0012:3
     22 YGO=(XO-XZ)/RATIO+YGZ                                           C  002:0014:3
        HPO=YW-YGO                                                      C  002:0016:5
        IF(XO.LT..95)GO TO 20                                           C  002:0018:1
        IF(XO.GT.1.05)GO TO 92                                          C  002:001A:4
        NACR=HPO/.0294*NAO                                              C  002:001D:4
     92 F=1.                                                            C  002:0021:1
        RATE=1.*HPO                                                     C  002:0021:5
        NMRATE=RATE/.0294                                               C  002:0023:0
        GO TO 40                                                        C  002:0025:4
     20 NACON=HPO/.0294*NAO                                             C  002:0026:1
        IF(J.EQ.1)GO TO 30                                              C  002:0029:1
        IF(I.EQ.1)GO TO 88                                              C  002:002A:2
        IF(NACR.LT.2.)GO TO 50                                          C  002:002B:3
        I=1                                                             C  002:002C:5
        F=.7                                                            C  002:002D:3
     88 A56=XO-1./IGBI-1.                                               C  002:002F:3
        B56=1./IGBI-2.*XO/(3.*NACON)                                    C  002:0031:3
        C56=2./(3.*NACON)                                               C  002:0034:4
        DO 11 K=1,10                                                    C  002:0036:3
        G=A56*F*F+B56*F+C56                                             C  002:0038:0
        GDIFF=2.*A56*F+B56                                              C  002:003B:2
        FSFNEW=G/GDIFF                                                  C  002:003D:4
        IF(ABS(FSFNEW).LT..0001)GO TO 12                                C  002:003F:0
        FNEW=F-FSFNEW                                                   C  002:0041:4
     11 F=FNEW                                                          C  002:0043:0
        GO TO 3                                                         C  002:0046:0
     12 NA=NACON*F                                                      C  002:0046:3
        CRIT=(1./IGBI+2./NA)/(1.+1./IGBI)                               C  002:0047:5
        IF(F.GT.CRIT)GO TO 100                                          C  002:004B:1
        J=1                                                             C  002:004C:3
     30 A64=1.+2./IGBI+1./(IGBI*IGBI)                                   C  002:004D:1
        B64=2./IGBI+2./(IGBI*IGBI)                                      C  002:0050:0
        C64=1./(IGBI*IGBI)-3.*XO/NACON                                  C  002:0052:4
        D64=2.*XO/(NACON*NACON)                                         C  002:0055:4
        DO 111 K=1,10                                                   C  002:0057:5
        G=A64*F*F*F-B64*F*F+C64*F+D64                                   C  002:0059:0
        GDIFF=3.*A64*F*F-2.*B64*F+C64                                   C  002:005E:2
        FSFNEW=G/GDIFF                                                  C  002:0062:4
        IF(ABS(FSFNEW).LT..0001)GO TO 100                               C  002:0064:0
        FNEW=F-FSFNEW                                                   C  002:0066:4
    111 F=FNEW                                                          C  002:0068:0
        GO TO 3                                                         C  002:0068:0
     50 A44=IGBI*IGBI+2.*IGBI+1.                                        C  002:006B:3
        B44=2.*IGBI+XO*IGBI*IGBI+2.                                     C  002:006E:0
        DO 211 K=1,10                                                   C  002:0071:2
        G=A44*F*F-B44*F+1.                                              C  002:0072:0
        GDIFF=2.*A44*F-B44                                              C  002:0075:1
        FSFNEW=G/GDIFF                                                  C  002:0077:3
        IF(ABS(FSFNEW).LT..0001)GO TO 100                               C  002:0078:5
        FNEW=F-FSFNEW                                                   C  002:007B:4
    211 F=FNEW                                                          C  002:007D:0
        GO TO 3                                                         C  002:0080:0
    100 RATE=F*HPO                                                      C  002:0080:3
        NMRATE=RATE/.0294                                               C  002:0081:5
     40 WRITE(6,33)XO,F,RATE,NMRATE,NACR,NACON,RATIO                    C  002:0083:4
                                                                              FIB IS 0006 LONG
     33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F8.4) C  002:0093:2
        IF(J.EQ.1)WRITE(6,522)                                          C  002:0093:2
        CONTINUE                                                        C  002:0098:2
        IF(XO.LE..2)GO TO 25                                            C  002:0098:2
        XO=XO-.1                                                        C  002:009A:4
        GO TO 22                                                        C  002:009D:4
```

```
  3 WRITE(6,200)X0                                                  C   002:009E:1
200 FORMAT(1X,'X0=',F4.2,10X,'NO CONVERGENCE')                     C   002:00A5:2
    IF(J.EQ.1)WRITE(6,522)                                          C   002:00A5:2
522 FORMAT(95X,'FRONT DISAPPEARED')                                 C   002:00AA:2
    GO TO 25                                                        C   002:00AA:2
222 STOP                                                            C   002:00AA:5
    END                                                             C   002:00AB:4
    002:00AF:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0000
                                                                    SEGMENT 002 IS 00BE LONG
```

```
          B6700/B7700   F O R T R A N   C O M P I L A T I O N   M A R K   2.7.480     MONDAY, 05/10/76     11:31 AM
C         COCURRENT DRYER*****NTU=1.5                                 C   000:0000:5
                                                                        START OF SEGMENT 002
          REAL NMRATE,NAO,NA,NACR,NACON                               C   002:0000:0
     25   READ(5,10,END=222)NAO,IGBI                                  C   002:0000:0
                                                                              FIB IS 0006 LONG
     10   FORMAT(F7.4,I2)                                             C   002:000A:0
          I=0                                                         C   002:000A:0
          J=0                                                         C   002:000A:4
          RATIO=100.                                                  C   002:000B:2
          YW=.0371                                                    C   002:000C:1
          YGO=.0077                                                   C   002:000E:3
          XO=1.5                                                      C   002:0010:3
          XZ=1.5                                                      C   002:0012:3
          YGZOLD=YGO                                                  C   002:0014:3
          YWOLD=YW                                                    C   002:0015:2
     22   YGZ=(XO-XZ)/RATIO+YGO                                       C   002:0016:1
          YW=YWOLD+(YGZ-YGZOLD)/1.134                                 C   002:0018:3
          HPO=YW-YGZ                                                  C   002:001B:5
          YGZOLD=YGZ                                                  C   002:001C:5
          YWOLD=YW                                                    C   002:001D:4
          IF(XZ.LT..995)GO TO 20                                      C   002:001E:3
          IF(XZ.GT.1.005)GO TO 92                                     C   002:0020:4
          NACR=HPO/.0294*NAO                                          C   002:0023:4
     92   F=1.                                                        C   002:0027:1
          RATE=1.*HPO                                                 C   002:0027:5
          TIP=1./RATE                                                 C   002:0029:0
          NMRATE=RATE/.0294                                           C   002:002A:1
          GO TO 40                                                    C   002:002C:4
     20   NACON=HPO/.0294*NAO                                         C   002:002D:1
          IF(J.EQ.1)GO TO 30                                          C   002:0030:1
          IF(I.EQ.1)GO TO 88                                          C   002:0031:2
          IF(NACR.LT.2.)GO TO 50                                      C   002:0032:3
          I=1                                                         C   002:0033:5
          F=.7                                                        C   002:0034:3
     88   A56=XZ-1./IGBI-1.                                           C   002:0036:3
          B56=1./IGBI-2.*XZ/(3.*NACON)                                C   002:0038:3
          C56=2./(3.*NACON)                                           C   002:003B:4
          DO 11 K=1,10                                                C   002:003D:3
          G=A56*F*F+B56*F+C56                                         C   002:003F:0
          GDIFF=2.*A56*F+B56                                          C   002:0042:2
          FSFNEW=G/GDIFF                                              C   002:0044:4
          IF(ABS(FSFNEW).LT..0001)GO TO 12                            C   002:0046:0
          FNEW=F-FSFNEW                                               C   002:0048:4
     11   F=FNEW                                                      C   002:004A:0
          GO TO 3                                                     C   002:004D:0
     12   NA=NACON*F                                                  C   002:004D:3
          CRIT=(1./IGBI+2./NA)/(1.+1./IGBI)                           C   002:004E:5
          IF(F.GT.CRIT)GO TO 100                                      C   002:0052:1
          J=1                                                         C   002:0053:3
     30   A64=1.+2./IGBI+1./(IGBI*IGBI)                               C   002:0054:1
          B64=2./IGBI+2./(IGBI*IGBI)                                  C   002:0057:0
          C64=1./(IGBI*IGBI)-3.*XZ/NACON                              C   002:0059:4
          D64=2.*XZ/(NACON*NACON)                                     C   002:005C:4
          DO 111 K=1,10                                               C   002:005E:5
          G=A64*F*F*F-B64*F*F+C64*F+D64                               C   002:0060:0
          GDIFF=3.*A64*F*F-2.*B64*F+C64                               C   002:0065:2
          FSFNEW=G/GDIFF                                              C   002:0069:4
          IF(ABS(FSFNEW).LT..0001)GO TO 100                           C   002:006B:0
          FNEW=F-FSFNEW                                               C   002:006D:4
    111   F=FNEW                                                      C   002:006F:0
          GO TO 3                                                     C   002:0072:0
     50   A44=IGBI*IGBI+2.*IGBI+1.                                    C   002:0072:3
          B44=2.*IGBI+XZ*IGBI*IGBI+2.                                 C   002:0075:0
          DO 211 K=1,10                                               C   002:0078:2
          G=A44*F*F-B44*F+1.                                          C   002:0079:0
          GDIFF=2.*A44*F-B44                                          C   002:007C:1
          FSFNEW=G/GDIFF                                              C   002:007E:3
          IF(ABS(FSFNEW).LT..0001)GO TO 100                           C   002:007F:5
          FNEW=F-FSFNEW                                               C   002:0082:4
    211   F=FNEW                                                      C   002:0084:0
          GO TO 3                                                     C   002:0087:0
    100   RATE=F*HPO                                                  C   002:0087:3
          NMRATE=RATE/.0294                                           C   002:0088:5
          TIP=1./RATE                                                 C   002:008A:4
     40   WRITE(6,33)XZ,F,RATE,NMRATE,NACR,NACON,RATIO,TIP            C   002:008B:5
```

```
                                                                                      FIB IS 0006 LONG
   33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F8.4     C   002:009D:2
     1,5X,F9.4)                                                          C   002:009D:2
      IF(J.EQ.1)WRITE(6,522)                                             C   002:009D:2
      CONTINUE                                                           C   002:00A2:2
      IF(XZ.LE..2)GO TO 25                                               C   002:00A2:2
      XZ=XZ-.1                                                           C   002:00A4:4
      GO TO 22                                                           C   002:00A7:4
    3 WRITE(6,200)XZ                                                     C   002:00A6:1
  200 FORMAT(1X,'XZ=',F4.2,10X,'NO CONVERGENCE')                         C   002:00AF:2
      IF(J.EQ.1)WRITE(6,522)                                             C   002:00AF:2
  522 FORMAT(95X,'FRONT DISAPPEARED')                                    C   002:00B4:2
      GO TO 25                                                           C   002:00B4:2
  222 STOP                                                               C   002:00B4:5
      END                                                                C   002:00B5:4
      002:0089:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:000D
                                                                           SEGMENT 002 IS 00C8 LONG
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```
      B6700/B7700   F O R T R A N   C O M P I L A T I O N   M A R K   2.7.480    MONDAY, 05/10/76    11:30 AM
C     COUNTERCURRENT DRYER****************                            C   000:0000:5
                                                                        START OF SEGMENT 002
      REAL NMRATE,NAO,NA,NACR,NACON                                   C   002:0000:0
   25 READ(5,10,END=222)NAO,IGBI                                      C   002:0000:0
                                                                            FIB IS 0006 LONG
   10 FORMAT(F7.4,I2)                                                 C   002:000A:0
      I=0                                                             C   002:000A:0
      J=0                                                             C   002:000A:4
      RATIO=100.                                                      C   002:000B:2
      YW=.0371                                                        C   002:000C:1
      YGZ=.0077                                                       C   002:000E:3
      XO=1.5                                                          C   002:0010:3
      XZ=.2                                                           C   002:0012:3
      YGZOLD=YGZ                                                      C   002:0014:3
      YWOLD=YW                                                        C   002:0015:2
   22 YGO=(XO-XZ)/RATIO+YGZ                                           C   002:0016:1
      YW=YWOLD+(YGO-YGZOLD)/1.134                                     C   002:0018:3
      HPO=YW-YGO                                                      C   002:001B:5
      IF(XO.LT..95)GO TO 20                                           C   002:001C:5
      IF(XO.GT.1.05)GO TO 92                                          C   002:001F:4
      NACR=HPO/.0294*NAO                                              C   002:0022:4
   92 F=1.                                                            C   002:0026:1
      RATE=1.*HPO                                                     C   002:0026:5
      NMRATE=RATE/.0294                                               C   002:0028:0
      GO TO 40                                                        C   002:002A:4
   20 NACON=HPO/.0294*NAO                                             C   002:002B:1
      IF(J.EQ.1)GO TO 30                                              C   002:002E:1
      IF(I.EQ.1)GO TO 88                                              C   002:002F:2
      IF(NACR.LT.2.)GO TO 50                                          C   002:0030:3
      I=1                                                             C   002:0031:5
      F=.7                                                            C   002:0032:3
   88 A56=XO-1./IGBI-1.                                               C   002:0034:3
      B56=1./IGBI-2.*XO/(3.*NACON)                                    C   002:0036:3
      C56=2./(3.*NACON)                                               C   002:0039:4
      DO 11 K=1,10                                                    C   002:003B:3
      G=A56*F*F+B56*F+C56                                             C   002:003D:0
      GDIFF=2.*A56*F+B56                                              C   002:0040:2
      FSFNEW=G/GDIFF                                                  C   002:0042:4
      IF(ABS(FSFNEW).LT..0001)GO TO 12                                C   002:0044:0
      FNEW=F-FSFNEW                                                   C   002:0046:4
   11 F=FNEW                                                          C   002:0048:0
      GO TO 3                                                         C   002:004B:0
   12 NA=NACON*F                                                      C   002:004B:3
      CRIT=(1./IGBI+2./NA)/(1.+1./IGBI)                               C   002:004C:5
      IF(F.GT.CRIT)GO TO 100                                          C   002:0050:1
      J=1                                                             C   002:0051:3
   30 A64=1.+2./IGBI+1./(IGBI*IGBI)                                   C   002:0052:1
      B64=2./IGBI+2./(IGBI*IGBI)                                      C   002:0055:0
      C64=1./(IGBI*IGBI)-3.*XO/NACON                                  C   002:0057:4
      D64=2.*XO/(NACON*NACON)                                         C   002:005A:4
      DO 111 K=1,10                                                   C   002:005C:5
      G=A64*F*F*F-B64*F*F+C64*F+D64                                   C   002:005E:0
      GDIFF=3.*A64*F*F-2.*B64*F+C64                                   C   002:0063:2
      FSFNEW=G/GDIFF                                                  C   002:0067:4
      IF(ABS(FSFNEW).LT..0001)GO TO 100                               C   002:0069:0
      FNEW=F-FSFNEW                                                   C   002:006B:4
  111 F=FNEW                                                          C   002:006D:0
      GO TO 3                                                         C   002:0070:0
   50 A44=IGBI*IGBI+2.*IGBI+1.                                        C   002:0070:3
      B44=2.*IGBI*XO*IGBI*IGBI+2.                                     C   002:0073:0
      DO 211 K=1,10                                                   C   002:0076:2
      G=A44*F*F-B44*F+1.                                              C   002:0077:0
      GDIFF=2.*A44*F-B44                                              C   002:007A:1
      FSFNEW=G/GDIFF                                                  C   002:007C:3
      IF(ABS(FSFNEW).LT..0001)GO TO 100                               C   002:007D:5
      FNEW=F-FSFNEW                                                   C   002:0080:4
  211 F=FNEW                                                          C   002:0082:0
      GO TO 3                                                         C   002:0085:0
  100 RATE=F*HPO                                                      C   002:0085:3
      NMRATE=RATE/.0294                                               C   002:0086:5
   40 WRITE(6,33)XO,F,RATE,NMRATE,NACR,NACON,RATIO                    C   002:0088:4
                                                                            FIB IS 0006 LONG
   33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F6.4) C   002:0098:2
      IF(J.EQ.1)WRITE(6,522)                                          C   002:0098:2
      CONTINUE                                                        C   002:009D:2
```

```
      IF(X0.LE..2)GO TO 25                                               C   002:009D:2
      X0=X0-.1                                                           C   002:009F:4
      GO TO 22                                                           C   002:00A2:4
    3 WRITE(6,200)X0                                                     C   002:00A3:1
  200 FORMAT(1X,'X0=',F4.2,10X,'NO CONVERGENCE')                         C   002:00AA:2
      IF(J.EQ.1)WRITE(6,522)                                             C   002:00AA:2
  522 FORMAT(95X,'FRONT DISAPPEARED')                                    C   002:00AF:2
      GO TO 25                                                           C   002:00AF:2
  222 STOP                                                               C   002:00AF:5
      END                                                                C   002:00B0:4
      002:0084:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0000
                                                                   SEGMENT 002 IS 00C3 LONG
```

```
C       COCURRENT DRYER******                                          .C  000:0000:5
                                                                       START OF SEGMENT 002
        REAL NMRATE,NAO,NA,NACR,NACON                                   C  002:0000:0
     25 READ(5,10,END=222)NAO,IGBI                                      C  002:0000:0
                                                                            FIB IS 0006 LONG
     10 FORMAT(F7.4,I4)                                                 C  002:000A:0
        I=0                                                             C  002:000A:0
        J=0                                                             C  002:000A:4
        RATIO=100.                                                      C  002:000B:2
        YW=.0302                                                        C  002:000C:1
        YGO=.0049                                                       C  002:000E:3
        XO=.26                                                          C  002:0010:3
        XZ=.26                                                          C  002:0012:3
        XCR=.13                                                         C  002:0014:3
     22 YGZ=(XO-XZ)/RATIO+YGO                                           C  002:0016:3
        HPO=YW-YGZ                                                      C  002:0018:5
        PI=XZ/XCR                                                       C  002:001A:1
        IF(PI.LT..995)GO TO 20                                          C  002:001B:3
        IF(PI.GT.1.005)GO TO 92                                         C  002:001D:4
        NACR=HPO/.0253*NAO                                              C  002:0020:4
     92 F=1.                                                            C  002:0024:1
        RATE=1.*HPO                                                     C  002:0024:5
        TIP=1./RATE                                                     C  002:0026:0
        NMRATE=RATE/.0253                                               C  002:0027:1
        GO TO 40                                                        C  002:0029:4
     20 NACON=HPO/.0253*NAO                                             C  002:002A:1
        IF(J.EQ.1)GO TO 30                                              C  002:002D:1
        IF(I.EQ.1)GO TO 88                                              C  002:002E:2
        IF(NACR.LT.2.)GO TO 50                                          C  002:002F:3
        I=1                                                             C  002:0030:5
        F=.7                                                            C  002:0031:3
     88 CONTINUE                                                        C  002:0033:3
        DO 11 K=1,10                                                    C  002:0033:3
        NA=NACON*F                                                      C  002:0035:0
        E=F*IGBI/(1.-F+F*IGBI)                                          C  002:0036:2
        ESQ=E*E                                                         C  002:0039:3
        EDIFF=E/(F*(1.-F+F*IGBI))                                       C  002:003A:2
        SQU1=NA*NA                                                      C  002:003D:3
        T=NA*F                                                          C  002:003E:4
        TSQ=T*T                                                         C  002:0040:0
        COMP2=1.-2.*E/T+2.*ESQ/TSQ-4.*ESQ*E/(5.*TSQ*T)                  C  002:0040:5
        COMP3=1.-2./NA+2./SQU1-4./(5.*NA*SQU1)                          C  002:0047:3
        G=ESQ*E*COMP2/COMP3-PI                                          C  002:004C:1
        GDIFF=(COMP3*(3.*ESQ*EDIFF-(8.*T*ESQ*E*EDIFF-4.*NA*ESQ*ESQ)/TSQ  C  002:004F:0
       1+(10.*TSQ*ESQ*ESQ*EDIFF-8.*NA*T*ESQ*ESQ*E)/(TSQ*TSQ)-(120.*TSQ*T C  002:0055:0
       2*ESQ*ESQ*E*EDIFF-120.*TSQ*NA*ESQ*ESQ*ESQ)/(25.*TSQ*TSQ*TSQ))-ESQ C  002:005C:5
       3*E*COMP2*(2./T-4./(T*NA)+12./(5.*NA*NA*T)))/(COMP3*COMP3)       C  002:0064:4
        FSFNEW=G/GDIFF                                                  C  002:006C:3
        IF(ABS(FSFNEW).LT..0001)GO TO 12                                C  002:006D:5
        FNEW=F-FSFNEW                                                   C  002:0070:4
     11 F=FNEW                                                          C  002:0072:0
        GO TO 3                                                         C  002:0075:0
     12 NA=NACON*F                                                      C  002:0075:3
        CRIT=2.*E/F                                                     C  002:0076:5
        IF(NA.GT.CRIT)GO TO 100                                         C  002:0078:4
        J=1                                                             C  002:007A:0
     30 CONTINUE                                                        C  002:007A:4
        DO 111 K=1,10                                                   C  002:007A:4
        NA=NACON*F                                                      C  002:007C:0
        E=F*IGBI/(1.-F+F*IGBI)                                          C  002:007D:2
        EDIFF=E/(F*(1.-F+F*IGBI))                                       C  002:0080:3
        SQU1=NA*NA                                                      C  002:0083:2
        COMP1=5.*SQU1*NA-10.*SQU1+10.*NA-4.                             C  002:0084:3
        G=SQU1*SQU1*F*E*E/COMP1-PI                                      C  002:0086:5
        GDIFF=(COMP1*(2.*E*SQU1*SQU1*F*EDIFF+5.*E*E*SQU1*SQU1)          C  002:008C:3
       1-E*E*SQU1*SQU1*NA*(15.*SQU1-20.*NA+10.))/(COMP1*COMP1)          C  002:0092:1
        FSFNEW=G/GDIFF                                                  C  002:0096:3
        IF(ABS(FSFNEW).LT..0001)GO TO 100                               C  002:0099:5
        FNEW=F-FSFNEW                                                   C  002:009C:4
    111 F=FNEW                                                          C  002:009E:0
        GO TO 3                                                         C  002:00A1:0
     50 F=.7                                                            C  002:00A1:3
        DO 211 K=1,10                                                   C  002:00A3:3
        E=F*IGBI/(1.-F+F*IGBI)                                          C  002:00A5:0
        EDIFF=E/(F*(1.-F+F*IGBI))                                       C  002:00A6:1
```

```
      G=F*E*E-PI                                                                 C   002:00AB:0
      GDIFF=2.*F*E*EDIFF*E*E                                                     C   002:00AD:2
      FSFNEW=G/GDIFF                                                             C   002:00B0:3
      IF(ABS(FSFNEW).LT..0001)GO TO 100                                          C   002:00B1:5
      FNEW=F-FSFNEW                                                              C   002:00B4:4
  211 F=FNEW                                                                     C   002:00B6:0
      GO TO 3                                                                    C   002:00B9:0
  100 RATE=F*HPU                                                                 C   002:00B9:3
      NMRATE=RATE/.0253                                                          C   002:00BA:5
      TIP=1./RATE                                                                C   002:00BC:4
   40 WRITE(6,33)PI,F,RATE,NMRATE,NACR,NACON,RATIO,TIP                           C   002:00BD:5
                                                                                       FIB IS 0006 LONG
   33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F8.4             C   002:00CF:2
     1,5X,F9.4)                                                                  C   002:00CF:2
      IF(J.EQ.1)WRITE(6,522)                                                     C   002:00CF:2
      CONTINUE                                                                   C   002:00D4:2
      IF(XZ.LE..02)GO TO 25                                                      C   002:00D4:2
      XZ=XZ-.01                                                                  C   002:00D6:4
      GO TO 22                                                                   C   002:00D9:4
    3 WRITE(6,200)PI                                                             C   002:00DA:1
  200 FORMAT(1X,'PI=',F4.2,10X,'NO CONVERGENCE')                                 C   002:00E1:2
      IF(J.EQ.1)WRITE(6,522)                                                     C   002:00E1:2
  522 FORMAT(95X,'FRONT DISAPPEARED')                                            C   002:00E6:2
      GO TO 25                                                                   C   002:00E6:2
  222 STOP                                                                       C   002:00E6:5
      END                                                                        C   002:00E7:4
      002:00EB:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:0000
                                                                             SEGMENT 002 IS 00FA LONG
```

```
        B6700/B7700   F O R T R A N   C O M P I L A T I O N   M A R K   2.7.480     MONDAY, 05/10/76    11:24 AM
C       COUNTERCURRENT DRYER****************                                         C   000:0000:5
                                                                                       START OF SEGMENT 002
        REAL NMRATE,NAO,NA,NACR,NACON                                                C   002:0000:0
     25 READ(5,10,END=222)NAO,IGBI                                                   C   002:0000:0
                                                                                           FIB IS 0006 LONG
     10 FORMAT(F7.4,I2)                                                              C   002:000A:0
        I=0                                                                          C   002:000A:0
        J=0                                                                          C   002:000A:4
        RATIO=100.                                                                   C   002:000B:2
        YW=.0371                                                                     C   002:000C:1
        YGZ=.0077                                                                    C   002:000E:3
        XO=1.5                                                                       C   002:0010:3
        XZ=.2                                                                        C   002:0012:3
     22 YGO=(XO-XZ)/RATIO+YGZ                                                        C   002:0014:3
        HPO=YW-YGO                                                                   C   002:0016:5
        IF(XO.LT..95)GO TO 20                                                        C   002:0018:1
        IF(XO.GT.1.05)GO TO 92                                                       C   002:001A:4
        NACR=HPO/.0294*NAO                                                           C   002:001D:4
     92 F=1.                                                                         C   002:0021:1
        RATE=1.*HPO                                                                  C   002:0021:5
        TIP=1./RATE                                                                  C   002:0023:0
        NMRATE=RATE/.0294                                                            C   002:0024:1
        GO TO 40                                                                     C   002:0026:4
     20 NACON=HPO/.0294*NAO                                                          C   002:0027:1
        IF(J.EQ.1)GO TO 30                                                           C   002:002A:1
        IF(I.EQ.1)GO TO 88                                                           C   002:002B:2
        IF(NACR.LT.2.)GO TO 50                                                       C   002:002C:3
        I=1                                                                          C   002:002D:5
        F=.7                                                                         C   002:002E:3
     88 CONTINUE                                                                     C   002:0030:3
        DO 11 K=1,10                                                                 C   002:0030:3
        NA=NACON*F                                                                   C   002:0032:0
        E=F*IGBI/(1.-F+F*IGBI)                                                       C   002:0033:2
        ESQ=E*E                                                                      C   002:0036:3
        EDIFF=E/(F*(1.-F+F*IGBI))                                                    C   002:0037:2
        SQU1=NA*NA                                                                   C   002:003A:3
        T=NA*F                                                                       C   002:003B:4
        TSQ=T*T                                                                      C   002:003D:0
        COMP2=1.-2.*E/T+2.*ESQ/TSQ-4.*ESQ*E/(5.*TSQ*T)                               C   002:003D:5
        COMP3=1.-2./NA+2./SQU1-4./(5.*NA*SQU1)                                       C   002:0044:3
        G=ESQ*E*COMP2/COMP3-XO                                                       C   002:0049:1
        GDIFF=(COMP3*(3.*ESQ*EDIFF-(8.*T*ESQ*E*EDIFF-4.*NA*ESQ*ESQ)/TSQ              C   002:004C:0
       1+(10.*TSQ*ESQ*ESQ*EDIFF-8.*NA*T*ESQ*ESQ*E)/(TSQ*TSQ)-(120.*TSQ*T             C   002:0052:0
       2*ESQ*ESQ*E*EDIFF-120.*TSQ*NA*ESQ*ESQ*ESQ)/(25.*TSQ*TSQ*TSQ))-ESQ             C   002:0059:5
       3*E*COMP2*(2./T-4./(T*NA)+12./(5.*NA*NA*T))))/(COMP3*COMP3)                   C   002:0061:4
        FSFNEW=G/GDIFF                                                               C   002:0069:3
        IF(ABS(FSFNEW).LT..0001)GO TO 12                                             C   002:006A:5
        FNEW=F-FSFNEW                                                                C   002:006D:4
     11 F=FNEW                                                                       C   002:006F:0
        GO TO 3                                                                      C   002:0072:0
     12 NA=NACON*F                                                                   C   002:0072:3
        CRIT=2.*E/F                                                                  C   002:0073:5
        IF(NA.GT.CRIT)GO TO 100                                                      C   002:0075:4
        J=1                                                                          C   002:0077:0
     30 CONTINUE                                                                     C   002:0077:4
        DO 111 K=1,10                                                                C   002:0077:4
        NA=NACON*F                                                                   C   002:0079:0
        E=F*IGBI/(1.-F+F*IGBI)                                                       C   002:007A:2
        EDIFF=E/(F*(1.-F+F*IGBI))                                                    C   002:007D:3
        SQU1=NA*NA                                                                   C   002:0080:2
        COMP1=5.*SQU1*NA-10.*SQU1+10.*NA-4.                                          C   002:0081:3
        G=SQU1*SQU1*F*E*E/COMP1-XO                                                   C   002:0085:5
        GDIFF=(COMP1*(2.*E*SQU1*SQU1*F*EDIFF+5.*E*E*SQU1*SQU1)                       C   002:0089:3
       1-E*E*SQU1*SQU1*NA*(15.*SQU1-20.*NA+10.))/(COMP1*COMP1)                       C   002:008F:1
        FSFNEW=G/GDIFF                                                               C   002:0095:3
        IF(ABS(FSFNEW).LT..0001)GO TO 100                                            C   002:0096:5
        FNEW=F-FSFNEW                                                                C   002:0099:4
    111 F=FNEW                                                                       C   002:009B:0
        GO TO 3                                                                      C   002:009E:0
     50 F=.7                                                                         C   002:009E:3
        DO 211 K=1,10                                                                C   002:00A0:3
        E=F*IGBI/(1.-F+F*IGBI)                                                       C   002:00A2:0
        EDIFF=E/(F*(1.-F+F*IGBI))                                                    C   002:00A5:1
        G=F*E*E-XO                                                                   C   002:00A8:0
        GDIFF=2.*F*E*EDIFF+E*E                                                       C   002:00AA:2
```

```
      FSFNEW=G/GDIFF                                                              C   002:00AD:3
      IF(ABS(FSFNEW).LT..0001)GO TO 100                                           C   002:00AE:5
      FNEW=F-FSFNEW                                                               C   002:00B1:4
  211 F=FNEW                                                                      C   002:00B3:0
      GO TO 3                                                                     C   002:00B6:0
  100 RATE=F*HPO                                                                  C   002:00B6:3
      TIP=1./RATE                                                                 C   002:00B7:5
      NWRATE=RATE/.0294                                                           C   002:00B9:0
   40 WRITE(6,33)X0,F,RATE,NWRATE,NACR,NACON,RATIO,TIP                            C   002:00BB:4
                                                                                      FIB IS 0006 LONG
   33 FORMAT(1X,F4.2,5X,F6.4,5X,F6.4,5X,F6.4,5X,F7.4,5X,F7.4,5X,F8.4              C   002:00CD:2
     1,5X,F9.4)                                                                   C   002:00CD:2
      IF(J.EQ.1)WRITE(6,522)                                                      C   002:00CD:2
      CONTINUE                                                                    C   002:00D2:2
      IF(X0.LE..2)GO TO 25                                                        C   002:00D2:2
      X0=X0-.1                                                                    C   002:00D4:4
      GO TO 22                                                                    C   002:00D7:4
    3 WRITE(6,200)X0                                                              C   002:00D8:1
  200 FORMAT(1X,'X0=',F4.2,10X,'NO CONVERGENCE')                                  C   002:00DF:2
      IF(J.EQ.1)WRITE(6,522)                                                      C   002:00DF:2
  522 FORMAT(95X,'FRONT DISAPPEARED')                                             C   002:00E4:2
      GO TO 25                                                                    C   002:00E4:2
  222 STOP                                                                        C   002:00E4:5
      END                                                                         C   002:00E5:4
      002:00E9:0  IS THE LOCATION FOR EXCEPTIONAL ACTION ON THE I/O STATEMENT AT 002:000D.
                                                                                   SEGMENT 002 IS 00F8 LONG
```

4.0 EXPERIMENTAL

4.1 APPARATUS

a. Rotary Dryer Drying Experiment

(i) Rotary Dryer

The brick particles were dried in a bench-scale rotary dryer. The dimension of the dryer is 750mm long and 100mm diameter. There are eight lifting flights in the barrel. There are speed controls, with which the speeds of revolution of the barrel and the rotary feeder can be varied. The speed range for:-

barrel = 0 - 10 rpm

rotary feeder = 0 - 17 rpm

The air is heated by 2kw heater; and the inlet temperature is kept at a set constant value by a thermostat to $0.3^{o}C$. The maximum inlet air temperature is $260^{o}C$. The air-flowrates are controlled by adjustable orifice plates in the suction line to the blower. The outlet solid is collected in a plastic beaker. The outlet air is passed through a cyclone which completely removes fines over 25μm in diameter.

(ii) Moisture Content Determination Balancc

An ohau balance is used to determine the moisture content of the inlet and outlet solids. The balance gives direct moisture content (dry basis) reading if an exactly 100gm sample is used. The scale reads to 0.1 gm.

(iii) Humidity Determination

The outlet air humidity is determined by gravimetric method. A sample of the outlet air is drawn by suction from a vacuum pump. The flowrate of air drawn is measured

LIST OF APPARATUS

(Fig. 2a, Rotary Dryer)

1. Vibratory hopper
2. Heater
3. Air blower
4. Rotary feeder
5. Rotary barrel
6. U-tubes (Silica Gel)
7. Rotameter
8. Cyclone
9. Adjustable Orifice Plate
10. Solid Collector

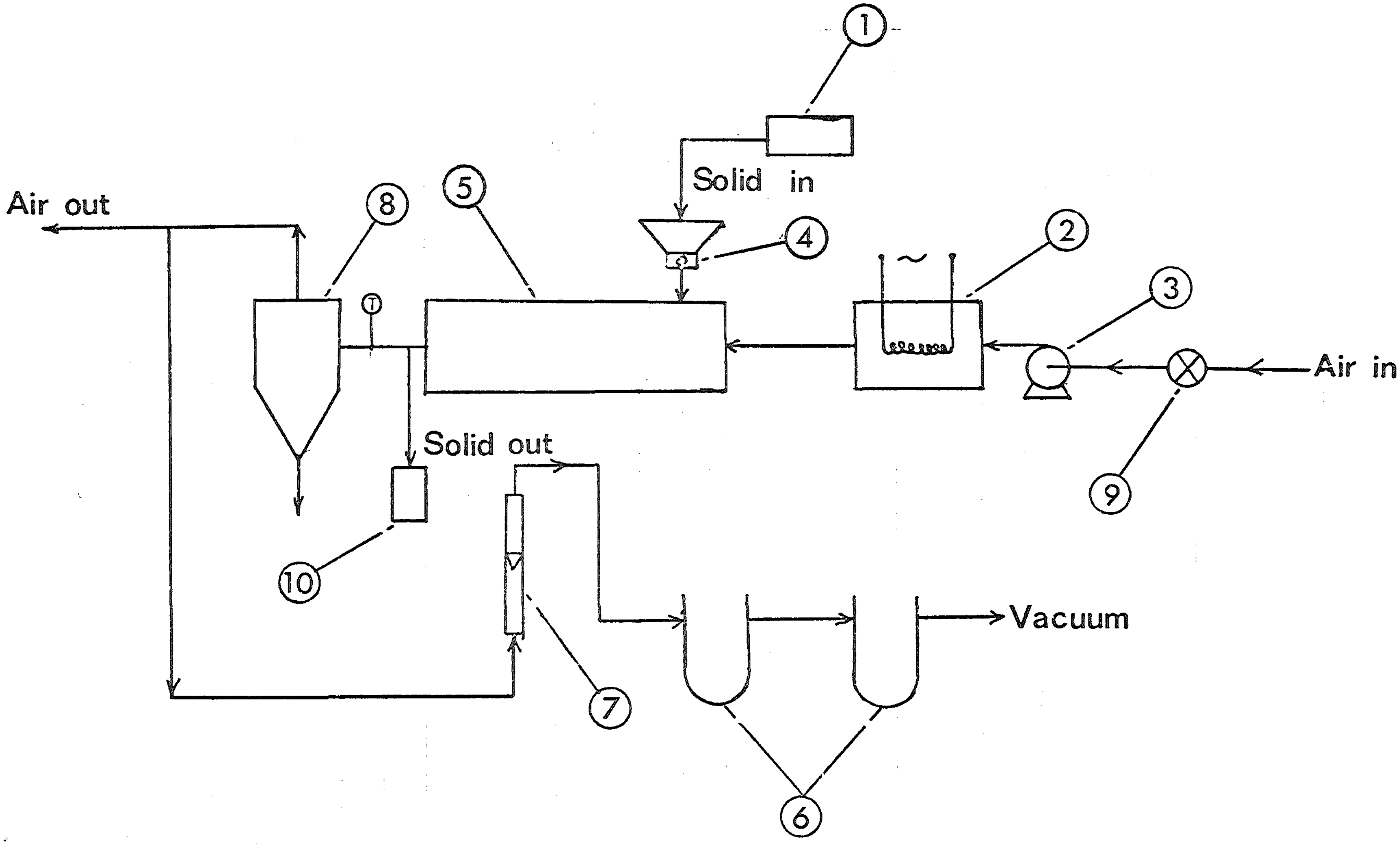


Fig. 2a : Line Diagram - Rotary Dryer

LIST OF APPARATUS

(Fig. 2b, Wind Tunnel)

1. Surge Tank
2. Air humidification column
3. Air supply fan
4. Variac controlled - heaters
5. Wet-bulb temperature measurement
6. Water heating element
7. Water recycle pump
8. Dry-bulb temperature measurement
9. Mettler H2OE balance
10. Servoscribe recorder
11. Suspended sample
12. Rotameter - water
13. Rotameter - air

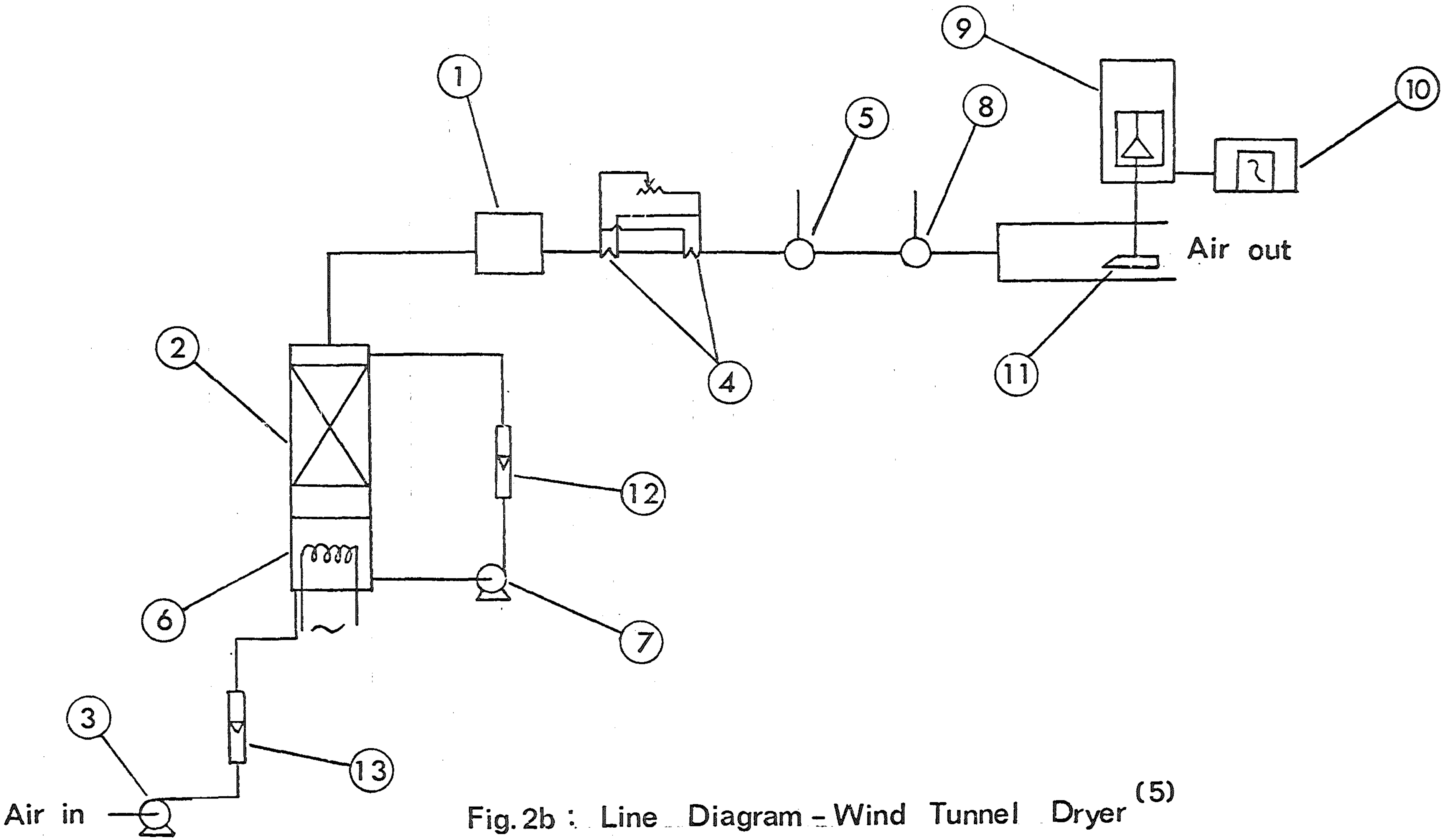


Fig. 2b : Line Diagram - Wind Tunnel Dryer [5]

Fig 2C Rotary Dryer

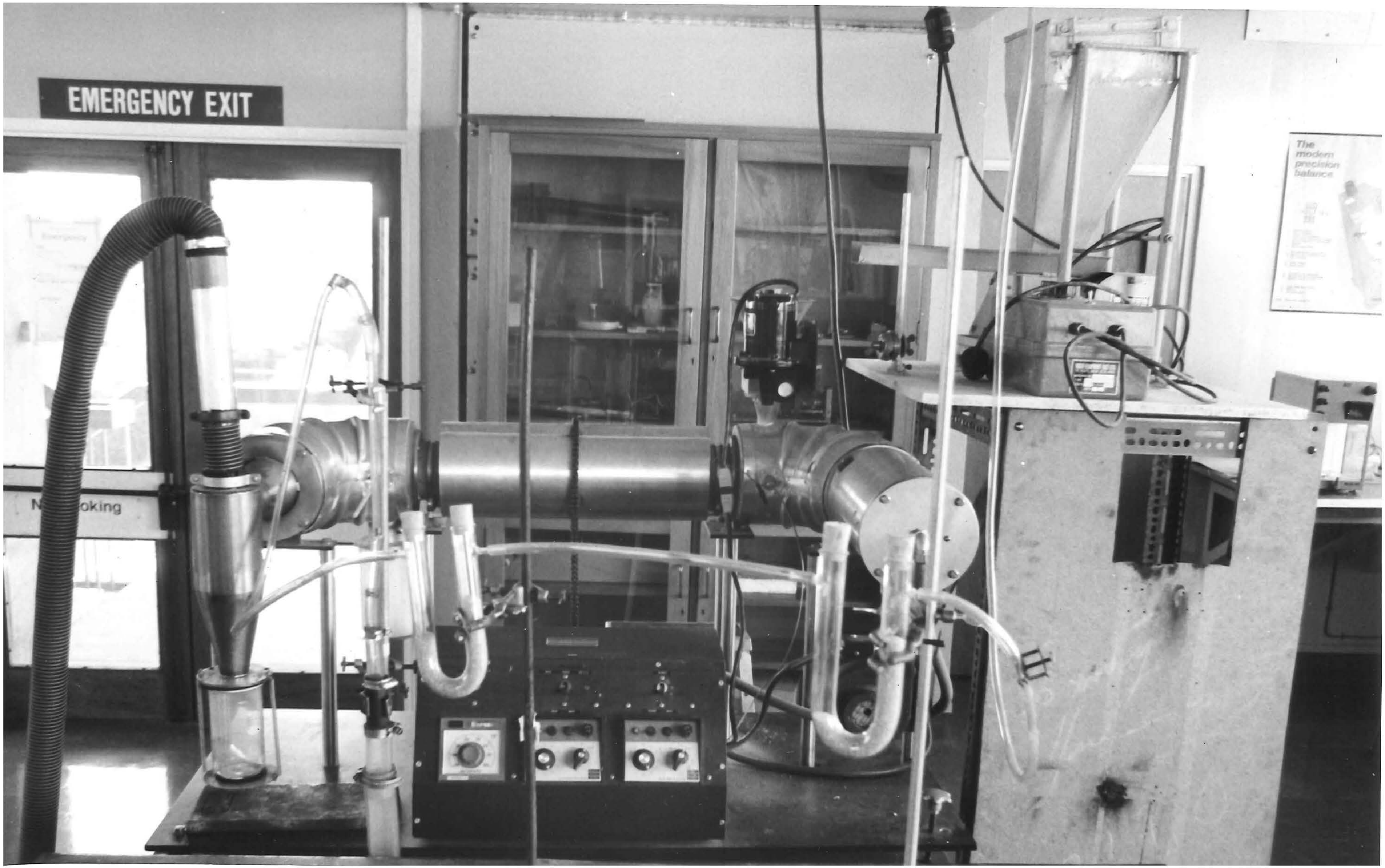
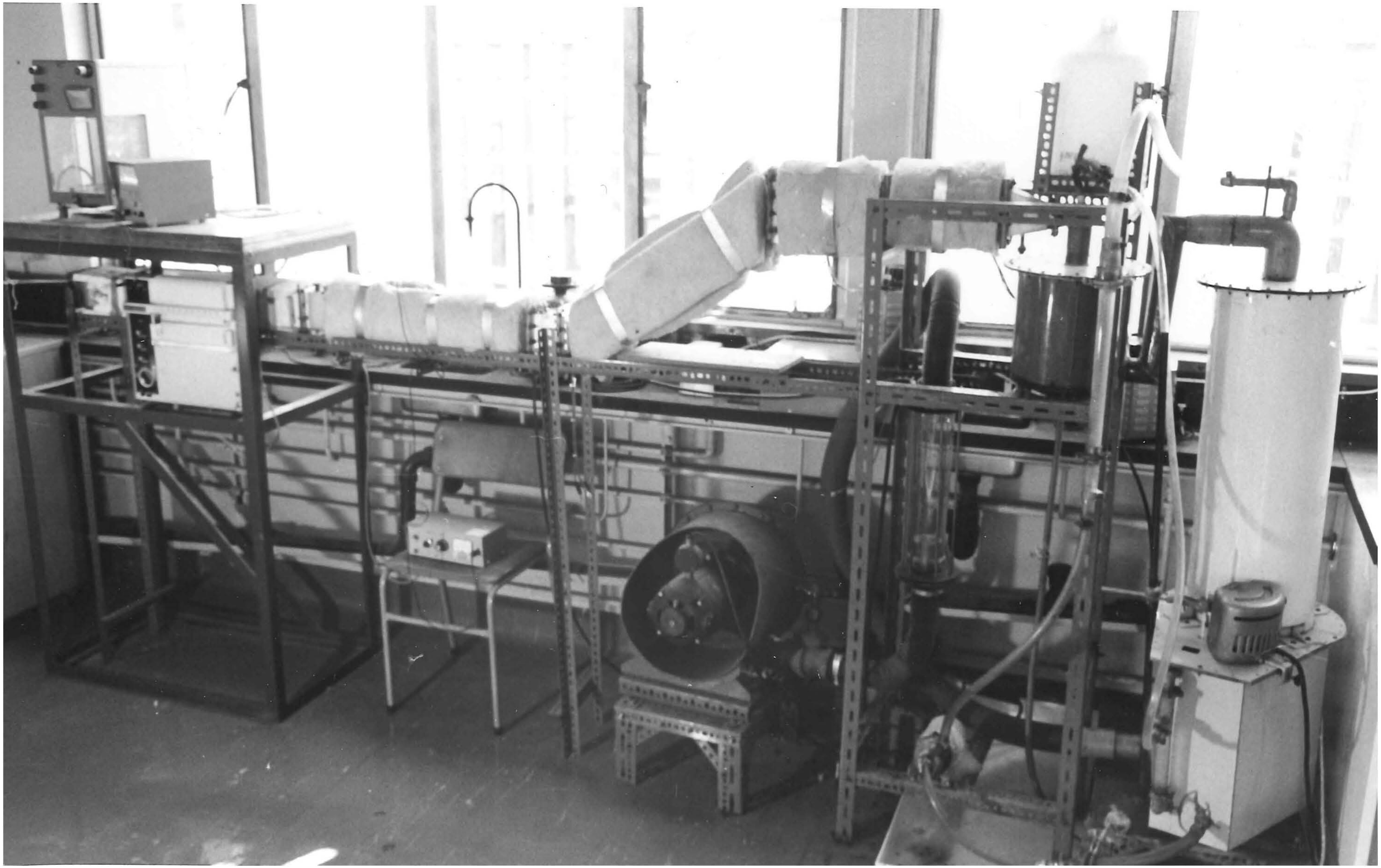

EMERGENCY EXIT
The modern precision balance

Fig. 2d Wind-tunnel dryer



by a metric 7 rotameter with a dural float. The moisture content of the outlet air is determined by the change in weight of the silica gel in the first U-tube over a period of about 7 minutes. The second u-tube containing silica gel is there to ensure if any back-flow of air occurs it will not affect the result of the first U-tube.

b. <u>Wind Tunnel Drying Experiments</u> (5)

This apparatus was used to dry the brick particles under constant external drying conditions.

(i) <u>Wind Tunnel</u>

The brick particles were dried in a wind tunnel. The humidification tower of Fig. 2a was not used. The dry-bulb temperature of the air can be increased by two Variac - controlled heating elements.

A venturi is used to provide a sufficiently large air velocity to give accurate wet-bulb temperature measurement. The measuring instrument is a mercury-in-glass thermometer with muslin wound round the bulb and the end of which is immersed in water. To ensure an even supply of air in the tunnel, the fan and the circulating water pump (not in use), were plugged into a voltage regulator. To enable the flows of air and circulating water to be changed, Variacs were used to control the supply voltage to both applicances.

(ii) <u>Moisture Content Determination</u>

The following air conditions were used:-

(i) wet-bulb temperature = 42.5^{o}C
(ii) dry-bulb temperature = 117^{o}C
(iii) air humidity = 0.026 kg
and (iv) maximum air velocity = 2.75 m/s.

The brick particles were packed in a single layer in a "streamlined boat" suspended on a rigid hook from a balance - Mettler 20 E - in the tunnel. The size of the "boat" is 130 mm x 65mm x 25mm, with a cavity of 38mm x 57mm x 12 mm. The reading on the balance was converted to a voltage signal and the output fed to a Smith servoscribe recorder.

The servoscribe recorder is calibrated to zero with the wet sample suspended. The recorder gives the change in weight due to the loss of moisture as drying takes place. The sample was weighed just prior to the beginning and at the end of the experiment on another balance. This fixed the total amount of moisture lost which corresponds to the maximum range of the recorder chart. The experiment is, therefore, stopped when the pen reaches the maximum point on the chart. The dried sample was then heated on the Ohau balance until there appeared to be no more moisture loss, and this was assumed to be the weight of the utterly dried sample. The moisture content on a dry basis was thus calculated.

4.2 EXPERIMENTAL PROCEDURE

a. Rotary Dryer Drying Experiment

(i) Moisture Adsorption

The brick particles were soaked in water in a beaker overnight. This ensures sufficient time for moisture adsorption equilibria to be achieved. The water is drained and the particles were put in a saturated atmosphere in a dessicator jar (water substituting the dessicant) kept at a constant temperature of 30^{o}C (just above atmospheric temperature) for about 30 minutes.

(ii) Initial Moisture Content

A sample of about 5 - 6 particles from the dessicator jar were put on the Ohau balance for moisture content determination. This is the inlet solid moisture content (dry basis).

(iii) Drying Experiment

The wet particles were lined up in single file in the channel of the vibrating hopper. Singular file is necessary to avoid congestion leading to the rotary feeder. The primary feeder was calibrated to feed about 6 particles/min.

The inlet air is heated to 93.3^{o}C. For steady state to be achieved, the air is heated until the outlet air temperature remains constant for about 20 minutes. The dryer is lagged so that adiabatic drying condition can be achieved. The estimated heat loss is 0.0278 Kw.

The outlet air humidity is measured after the experiment has run for about 5 minutes, in this time it is assumed that experimental steady state has occurred. To enable the total amount of air withdrawn to be calculated, the total time that the air is being drawn through the silica gel was noted. This is between 5 - 7 minutes.

A sample of particles from the outlet solid collector is put on the Ohau balance for moisture determination. This is the outlet solid moisture content (dry basis). The outlet air temperature is noted at the same time.

The following readings were taken during this experiment (see Appendice 7.5):-

1. inlet solid moisture content (dry basis),

2. Outlet solid moisture content (dry basis),
3. weight of silica gel + U-tube before passage of air,
4. weight of silica gel + U-tube after passage of air,
5. time of passage of air,
6. rotameter reading,
7. inlet air temperature,

and 8. outlet air temperature.

b. <u>Wind Tunnel Drying Experiment</u>

The heaters and air supply were adjusted until a suitable dry-bulb temperature is achieved. Steady state is assumed when the wet-bulb and dry-bulb temperatures remain constant for about 10 minutes.

The wet sample plus "boat" is weighed on a Mettler H18 balance. The sample is hung on the balance and the recorder is zeroed with the balance fully released. This is the tare weight.

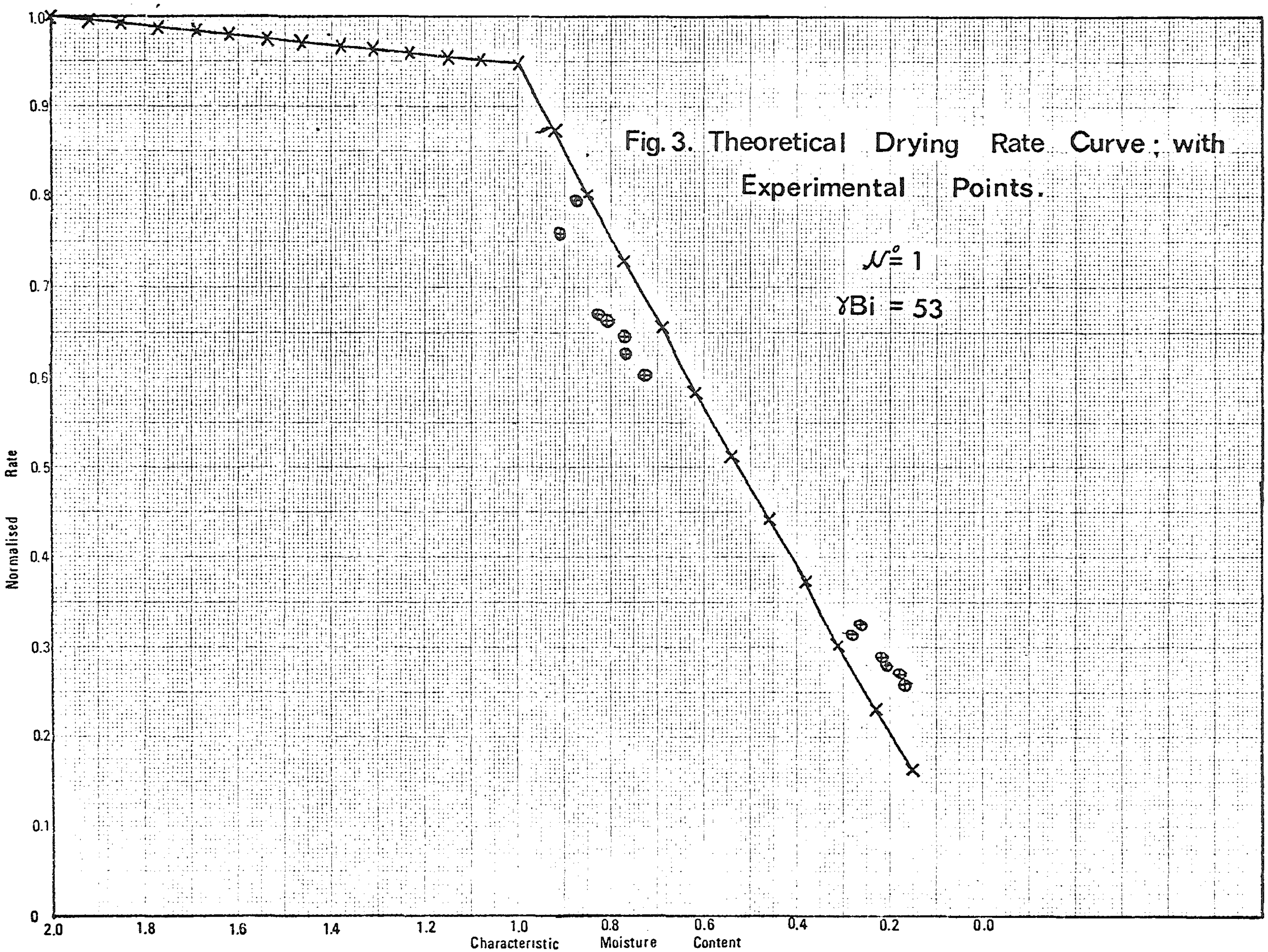
The experiment is stopped when the pen reaches the maximum point on the chart. The dried particles is put on the Ohau balance and heated until no further moisture loss is apparent. The utterly dried particles were weighed. The moisture content (dry basis) is thus calculated. The plot on the recorder, Fig. 4, is a plot of moisture content (dry basis) Vs. time.

The following reading were noted (see Appendice 7.8) during this part of the experiment:-

1. rotameter reading (air flowrate),
2. variac settings for heaters,
3. wet-bulb temperature,
4. dry-bulb temperature,
5. weight of wet particles + "boat"

6. weight of dried particles + "boat",

and 7. weight of utterly dried particles.



20 x 26 cm., In mm

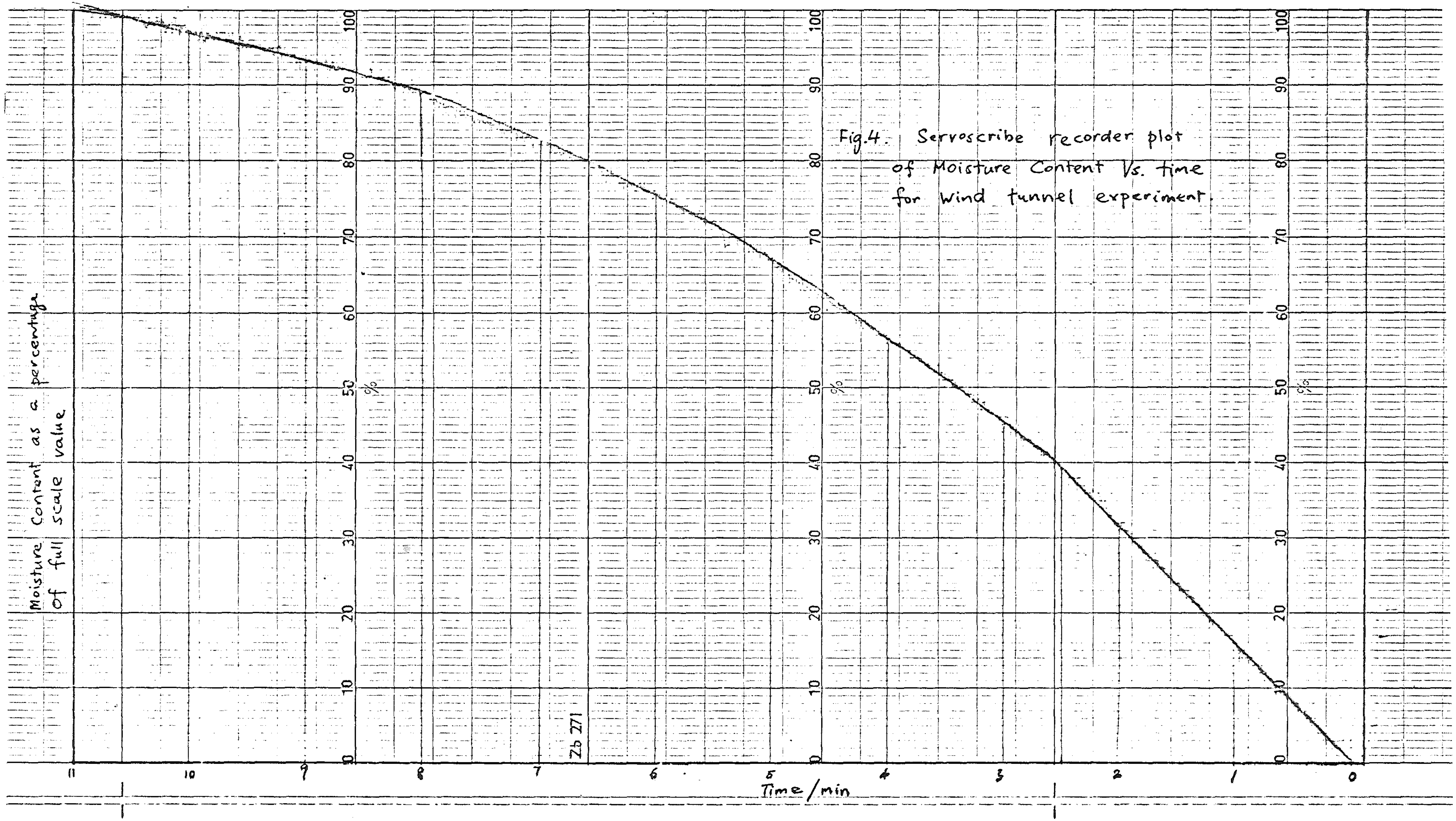
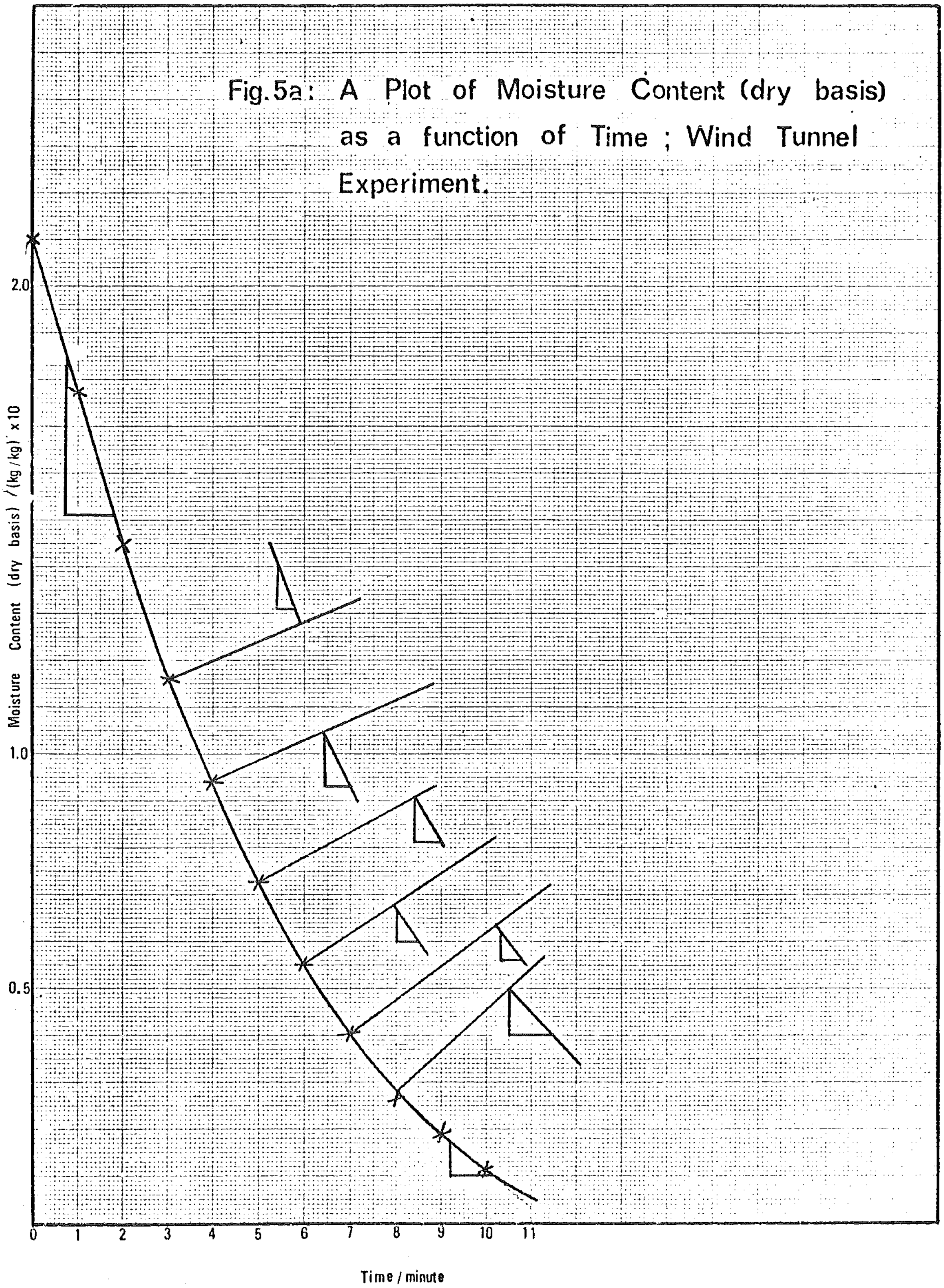
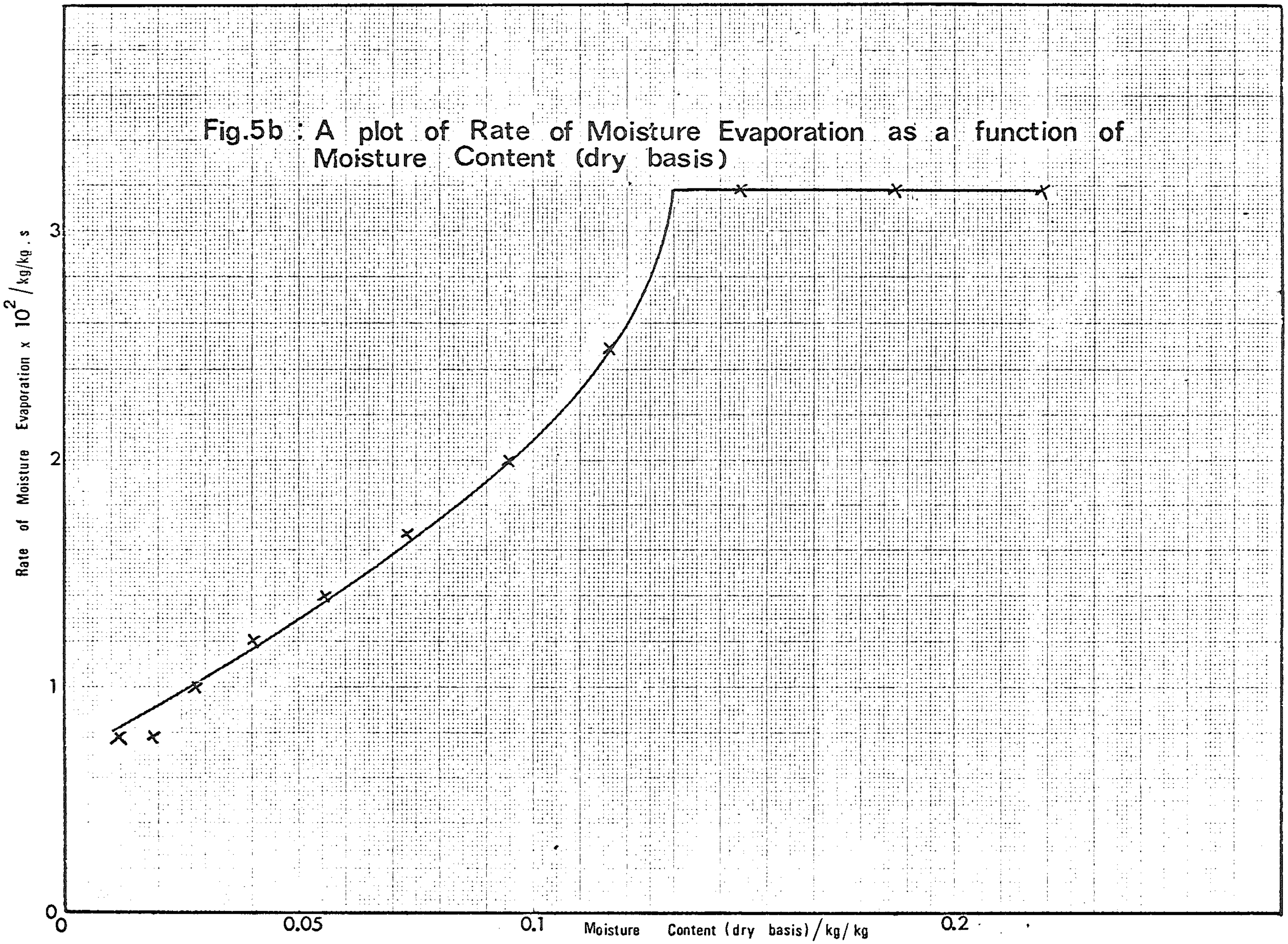


Fig.4. Servoscribe recorder plot of Moisture Content Vs. time for wind tunnel experiment.

20 x 26 cm., in mm





20 x 26 cm., In mm

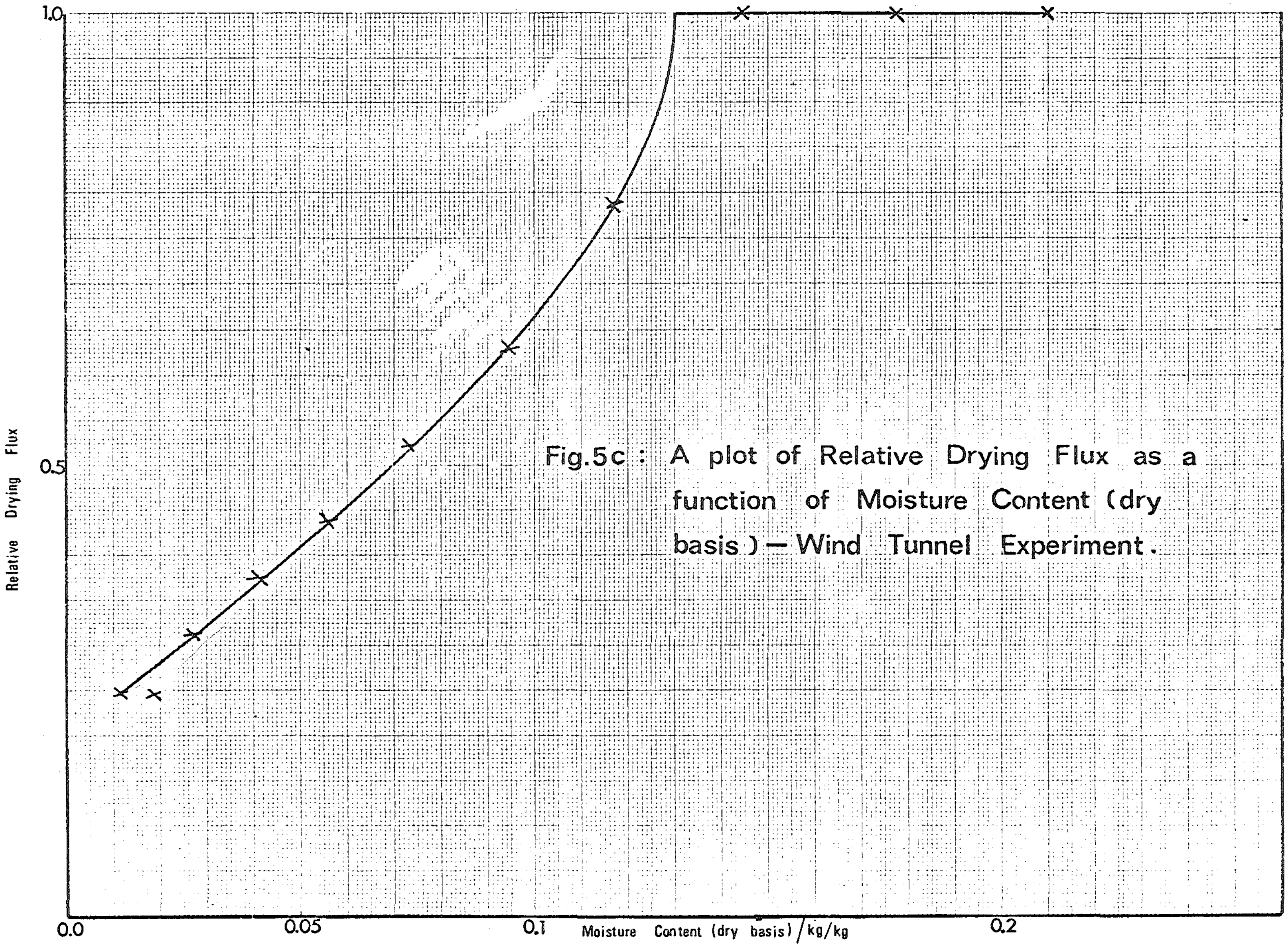


Fig.5c : A plot of Relative Drying Flux as a function of Moisture Content (dry basis) — Wind Tunnel Experiment.

5.0 DISCUSSION

The experiment was carried out in the slow drying regime. It will be difficult to run the experiment under fast drying because, firstly, the particles are the largest the rotary feeder can handle without causing problems; secondly, a higher wet-bulb temperature (say, 80°C) will be required and this will cause serious heat loss problem leading to non-adiabatic drying; thirdly, with resulting low solid outlet solid moisture content, the moisture determination will be inaccurate.

The wet particles entered the dryer at a moisture content below the critical point. To enable the constant falling rate part of the characteristic drying curve to be obtained, the dryer is imagined to be extended. By assuming an arbitrary value of inlet particles moisture content ($X = 0.26$) into the extended dryer, a mass balance will give the inlet humidity. In this approach, the inlet to the actual dryer was used as an experimental point.

An average inlet solid moisture content has to be taken because the present technique is not sophisticated enough to maintain similar inlet condition for every run.

From simple algebraic manipulation (Appendices 7.4), a locus of points of disappearance of the drying front was obtained. The significance of this locus is that it divides the drying rate profile into two points; above it a drying front still prevails, and below it the drying front has disappeared. (See Fig, A1).

One of the main problems faced was the particle feeding system. The problem can be attributed to the low feed-rate coupled with the inappropriateness of the rotary feeder for handling hard, brittle material. A vibratory hopper was needed to prefeed the particles gradually into the rotary feeder.

There was moisture lost when the wet particles were waiting on the primary feeder. The rate of moisture loss is 0.00076 gm/min.particle; giving a maximum error of ±0.01 kg/kg in the initial moisture content for a 20 minutes run.

The dryer was not perfectly adiabatic, there was an actual temperature drop of about 2.5^{o}C under no load conditions along the dryer. This is not expected to significantly affect the results. The inlet air temperature was 93.3^{o}C.

The relative drying flux curve (see Fig. 5C) under constant external conditions was determined experimentally by drying brick particles packed in a single layer in a "streamlined boat" in a drying tunnel which was maintained at constant external drying condition. The accuracy of the pen-recorder is about ±2% of full scale deflection. The rate of drying curve (Fig. 5b) shows resemblance to typical drying curves for the drying of porous, non-hygroscopic material (3). An experimental value of the critical moisture content of 0.13 was deduced from the drying curve and was used in experimental calculations.

The experimental results (Appendices 7.1, 7.2 and 7.3) were based on parameters γBi and $\mathcal{N}^{o}$ of 53 and 1.00 respectively. The experimental points shown in Fig. 3 appear to agree well with the general trend of the theory. The drying is in the slow drying regime, that is, $\mathcal{N}_{cr}$ is less than 2. Strictly speaking, the intensity of drying, $\mathcal{N}$, can be increased by increasing the size of the particles and not require an increase in the rate of moisture evaporation. The theoretical characteristic drying curves for the drying of a slab of infinite extent and spherical particles are shown in Appendices 7.9.

6.0 CONCLUSION

The experimental results verify the theoretical characteristic drying curve for the drying of spherical particles under adiabatic, co-current flow, only in the low intensity regime.

The results appear to follow the general trend of the theory developed by Keey and Suzuki (see Fig. 3), thus, we have ascertained the validity of the theory. It is reasonable to believe that the theory can be verified with the same results for drying in the high intensity regime.

The theory based on the drying of a slab of infinite extent was not experimentally verified. It is concluded that the theory will hold under experimental test, on the basis that both theories were essentially based on the same assumptions.

7.0 APPENDIX

APPENDICE 7.1

To calculate the value of parameters, γBi and $\mathcal{N}^{o}$.

(i) Calculation - γBi.

= Volumetric overall heat transfer coefficient

= 200 $Wm^{-3}\ K^{-1}$ (p 313, reference 3)

t_s = surface temperature

= 20^oC

t_a = air temperature

= 93^oC

L = length of dryer

= 0.75m

d = diameter of dryer

= 0.1m

S = cross sectional area of dryer

$$= \frac{\Pi d^2}{4}$$

$$= \frac{\Pi}{400}\ m^2$$

V = volume of dryer

= S.L

$$= \frac{3\Pi}{1600}\ m^3$$

Heat balance.

$$W.\Delta H_V = U.V.\Delta T$$

where W is rate of moisture evaporation (kg/s) and

ΔH_V (= $2x10^3$kJ/kg) is the heat of vaporisation of water.

$$\therefore \quad W = \frac{U.V.\Delta T}{\Delta H_v}$$

$$= \frac{200}{2x10^6} \cdot \frac{3\,\Pi}{1600} \cdot 77$$

$$= 45.36 \times 10^{-6} \text{ kg/s}$$

A_p = Area of particle

$$= \frac{6}{d_p} \cdot V_p$$

From feedrate, we obtain,

hold-up = 0.266%

$$\therefore \quad V_p = 0.00266 \times V \text{ m}^3$$

$$\therefore \quad A_p = \frac{6}{0.01} \cdot 0.00266 \cdot \frac{3\Pi}{1600} \text{ m}^2$$

$$= 9.4 \times 10^{-3} \text{ m}^2$$

From heat transfer equation,

h_c = heat transfer coefficient

$$= \frac{U.V}{A_p}$$

$$= 200 \; \frac{3\Pi}{1600} \cdot \frac{1}{9.4x10^{-3}}$$

$$= 125 \quad W/m^2K$$

We can obtain the mass transfer coefficient for humidity differences from the psychrometric ratio,

$$\frac{C_p K_y}{h_c} \simeq 1$$

if the drying process takes place under low humidities, where,

K_y - mass transfer coefficient for humidity differences ($kg/m^2.s$)

and C_p - Heat capacity of dry gas

$= 1 \text{ kJ kg}^{-1}K^{-1}$.

$$\therefore \quad K_y = \frac{h_c}{C_p}$$

$$= \frac{125}{103} \left(\frac{J}{sm^2K} \cdot \frac{kg.K}{J} \right)$$

$$= 1.25 \times 10^{-1} \ kg/m^2s$$

Keey (6) has derived a formula for calculating Biot Number consistent with the theory of reference 1.

$$\text{Biot Number} = \frac{K_y \ b}{M_B \ D_a}$$

Where M_B = density of air (kg/m^3)

Krischer (7) gives $\mu_d = 9.3$ for brick of density 1637-1860 kgm^{-3}.

Schirmer's formula, Krisher (7), pg 175.

$$D_{ab} = \frac{0.083}{3600} \cdot \frac{P}{10000} \left(\frac{T}{273} \right)^{1.81} m^2s^{-1}$$

Where P = pressure

T = particle temperature

Particle temperature $\simeq 50^oC$

$$\therefore \quad D_{ab} = \frac{0.083}{3600} \left(\frac{323}{273} \right)^{1.81} m^2s^{-1}$$

$$= 31.2 \times 10^{-6} \ m^2s^{-1}$$

$$\rho = 1.293 \times \left(\frac{273}{323} \right) = 0.946 \ kgm^{-3}$$

$$K_y = 0.125 \ kgm^{-2}s^{-1}$$

$$\therefore \quad Bi = \frac{K_y b \mu_d}{\rho D_{ab}} = \frac{0.125 \times 5 \times 10^{-3} \times 9.3}{0.946 \times 31.2 \times 10^{-6}}$$

$$= \underline{197}$$

$\gamma = 0.27$ (at Tw = 35^o, β=0.1) (reference 1)

$$\therefore \quad \gamma Bi = 0.27 \times 197$$

$$= 53$$

Particle temperature $\approx$ 50°C

$$\therefore \quad D_{ab} = \frac{0.083}{3600}\left(\frac{323}{273}\right)^{1.81} \quad m^2s^{-1}$$

$$= 31.2 \times 10^{-6}\ m^2s^{-1}$$

$$\rho = 1.293 \times \left(\frac{273}{323}\right) = 0.946\ kgm^{-3}$$

$$K_y = 0.125\ kgm^{-2}s^{-1}$$

$$\therefore \quad Bi = \frac{K_y b\mu d}{\rho D_{ab}} = \frac{0.125 \times 5 \times 10^{-3} \times 9.3}{0.946 \times 31.2 \times 10^{-6}}$$

$$= \underline{197}$$

$\gamma = 0.27$ (at $T_w = 35^o$, $\beta = 0.1$) (reference 1)

$$\therefore \quad \gamma Bi = 0.27 \times 197$$

$$\approx 53$$

(ii) Calculation $-\mathcal{N}^o$

R - radius of particle

$= 5 \times 10^{-3}m$

D_a = apparent diffusion coefficent for moisture movement through wet material (m^2s^{-1}), see below

X_o = moisture content

= 0.26 kg/kg dry solid

ρ_s = density of solid

= 1700 kg/m ^{3}

$N_a^o = fK_y\psi(Y_w - Y_{GO})$

$= 1 \times 1.25 \times 10^{-1} \times 0.9438 \times 0.0253$

$= 2.985 \times 10^{-3}\ kg/m^2s$

Thermal Diffusivity of red brick $= 18.2\times10^{-4}m^2h^{-1}$

$(\rho = 1700 \text{ kg m}^{-3})$ $= 5.05\times10^{-7}m^2s^{-1}$

Thermal diffusivity of Kaolin (porous clay)

$= 16.1\times10^{-4}m^2h^{-1}$

Moisture diffusivity of Kaolin $X = 0.1,\ T = 45^oC$

$= 11.0\times10^{-5}m^2h^{-1}$

$= 3.05\times10^{-8}m^2s^{-1}$

Luikov number is independent of composition (justified since difference in K is small between red brick and Kaolin).

$$D_{\text{red brick}} = K_{\text{red brick}}\left(\frac{D}{K}\right)_{\text{Kaolin}}$$

$$= 18.2\ \frac{3.05 \times 10^{-8}}{16.1}$$

$$= 3.45\times10^{-8}\ m^2s^{-1}$$

The intensity criterion is derived from considering the variation of moisture content over the moist part.

$$N_a^o = fK_Y\ (Y_W - Y_G)$$

$$= 1 \times 1.25 \times 10^{-1} \times 0.9438\times0.0253$$

$$= 2.985\times10^{-3}\ kg/m^2s$$

$$\therefore \mathcal{N} = \frac{N_a^oR}{X_o\rho_sD_a}$$

$$= \frac{2.985 \times 10^{-3}\times5\times10^{-3}}{0.26 \times 1700 \times 3.45\times10^{-8}}$$

$$= \underline{0.98}\quad (\tilde{}1.0)$$

Appendices 7.2

To determine the drying fluxes based on experimental data of RUN 2.

Calculation

Moisture gained by silica gel = 173.8 - 173.55

= 0.25 gm.

Air mass flowrate (wet)

= 7.7 x 0.49 x 9.7 gm/min

= 36.6 gm/min

Air mass flowrate (dry)

= (36.6 - 0.25) gm/min

= 36.35 gm/min

$\therefore$ humidity of outlet air $= \dfrac{0.25}{36.35} \dfrac{\text{kg}}{\text{kg dry air}}$

$= 0.00688$ kg/kg

The dry bulk temperature at the outlet,

$T_G = 89.5^{\circ}C$.

From the adiabatic saturation line we obtain the following,

T_{GO} - dry bulb temperature at inlet

$= 93.3^{\circ}C$

$\therefore$ Y_{GO} = humidity at inlet

= 0.00505 kg/kg

From Fig. 4c, we obtained the following values of relative drying fluxes for the respective moisture content.

X_O = inlet moisture content (dry basis)

= 0.120 kg/kg (f_C = 0.26)

X_z = outlet moisture content (dry basis)

= 0.0285 kg/kg (f_z = 0.09)

Thus, the drying fluxes are,

$$\alpha f_o(Y_w - Y_{GO}) = 0.26\ (0.02975 - 0.00505)\alpha$$
$$= 0.00642\alpha$$

and
$$\alpha\, f_z(Y_w - Y_{GZ}) = 0.09\ (0.02975 - 0.00688)\alpha$$
$$= 0.00206\,\alpha$$

Where α is a coefficient

Appendice 7.3

To determine the solid feed rate for a given solid/gas ratio.

Calculation

Air velocity = 275 ft min^{-1}

Cross-sectional area of dryer $= \frac{\pi}{4} d^2$

$= \frac{\pi}{4} (\frac{1}{9}) = 0.08727 \text{ ft}^2$

Volumetric flowrate = 0.08727 x 275 cu.ft/min

= 24 cu. ft/min

Density of air at 200°F: = 0.06 lb/cu.ft

$\therefore$ Mass Density = 0.06 x 24 lb/min

= 1.44 lb/min

= 0.653 kg/min

solid/gas ratio $= \frac{G}{L} = 100$

$\therefore \quad L = \frac{G}{100} = \frac{653}{100}$

= 6.53 g/min

Average weight / particle = 1.1414 g

$\therefore$ No. of particles $= \frac{6.53}{1.1414}$

= 6 particles / min.

Appendice 7.4

To determine the locus of the points of disappearance of drying front.

The drying front disappear when $\delta = 1$.
Therefore, expression (3.21) becomes,

$$1 - \frac{(1-f)}{f\gamma Bi} = \frac{2}{\mathcal{N}f} \qquad \text{(A1)}$$

The characteristic drying curve expression for high intensity drying is,

$$\Phi = \frac{1 - (1-f)/f\gamma Bi - 2/3\mathcal{N}f}{1 - 2/3\mathcal{N}} \qquad \text{(A2)}$$

Substituting A1 to A2 gives,

$$\Phi = \frac{2}{\mathcal{N}f} \quad \frac{2}{3\mathcal{N}f} \qquad \text{(A3)}$$

$$= \frac{4}{3\mathcal{N}f} \,/ \left(1-\frac{2}{3\mathcal{N}}\right) \qquad \text{(A4)}$$

We obtain from equation (3.5),

$$\mathcal{N} = \frac{f(Y_W - Y_G)}{Y_W - Y_{GO}} \mathcal{N}^{o} \qquad \text{(A5)}$$

or, $\mathcal{N} = N_m \mathcal{N}^{o}$ (A6)

Where, N_m = normalised flux with respect to the rate at solid inlet to the co-flux adiabatic dryer.

$\therefore$ from expression (A4),

$$\Phi = \frac{4}{f(3N_m\mathcal{N}^{o} - 2)} \qquad \text{(A7)}$$

Multiply both sides of (A8) by $\dfrac{(Y_w - Y_{GO})}{(Y_w - Y_G)}$

then,

$$\left(\frac{Y_w - Y_{GO}}{Y_w - Y_G}\right) = \frac{4}{f(3N_m{}^{o} - 2)\left(\dfrac{Y_w - Y_G}{Y_w - Y_{GO}}\right)} \tag{A9}$$

but, $$f\frac{(Y_w - Y_G)}{(Y_w - Y_{GO})} = N_m \tag{A10}$$

therefore,

$$\Phi\left(\frac{Y_w - Y_{GO}}{Y_w - Y_G}\right) = \frac{4}{N_m\ (3N_m\psi^{o} - 2)} \tag{A11}$$

By overall mass balance,

$$Y = \frac{X_o - X}{\frac{G}{L}} + Y_{GO} \tag{A12}$$

Therefore, substituting Y_g gives,

$$\frac{Y_w - Y_G}{Y_w - Y_{GO}} = 1 - \frac{X_o - X}{\frac{G}{L}(Y_w - Y_{GO})} \tag{A13}$$

Let $$A = \frac{1}{\frac{G}{L}\ (Y_w - Y_{GO})} \tag{A14}$$

therefore, expression (A13) becomes,

$$\frac{Y_w - Y_G}{Y_w - Y_{GO}} = 1 - A\ (X_o - X) \tag{A15}$$

Substituting (A15) is (A11) gives,

$$\frac{\Phi}{1 - A\ (X_o - X)} = \frac{4}{N_m\ (3N_m\psi^{o} - 2)} \tag{A16}$$

from which we obtain the locus of a adiabatic, co-current dryer to be,

$$3\psi^{o}\Phi N_m{}^2 - 2\Phi N_m - 4\ (1 - A(X_o - X)) = 0 \tag{A17}$$

Similarly, an adiabatic, counter-flow case; the locus is,

$$3\Phi\mathcal{N}^{\circ}N_m^2 - 2\Phi N_m - 4\,(1-A(X - X_Z)) = 0 \qquad \text{(A18)}$$

For isothermal drying, the loci for co-current and countercurrent dryers are respectively,

$$3\Phi\mathcal{N}^{\circ}N_m^2 - 2\Phi\,N_m - 4B = 0 \qquad \text{(A19)}$$

$$\text{Where } B = \frac{Y_w - Y_{GZ}}{Y_w - Y_{GO}} \qquad \text{(A20)}$$

$$\text{and } 3\Phi\,\mathcal{N}^{\circ}N_m^2 - 2\Phi\,N_m - 4C = 0 \qquad \text{(A21)}$$

$$\text{Where } C = \frac{Y_w - Y_G}{Y_w - Y_{GO_{Co}}}$$

Appendices 7.5: Experimental Results (Rotary dryer experiment)

RUN	Wt. of Silica gel/gm before	Wt. of Silica gel/gm after	Time/min	Rotameter reading F.F = 9.7gm/min	Moisture Content (dry basis) X_o	Moisture Content (dry basis) X_z
1	179.76	180.16	7.29	15.2 (62%F.F)	0.105	0.0286
2	173.55	173.80	7.70	10.8 (49%F.F)	0.120	0.0285
3	178.75	179.11	7.47	12.3 (52.5%F.F)	0.108	0.0361
4	180.44	180.83	7.48	19.0 (75.5%F.F)	0.118	0.0233
5	171.44	172.00	5.85	13.0 (55.5%F.F)	0.1	0.0347
6	179.73	179.92	4.62	13.2 (56%F.F)	0.095	0.0266
7	174.36	174.65	5.53	15.0 (62%F.F)	0.1	0.0222

	Temperatures Inlet $T_{GO}/^{\circ}C$	Temperatures Outlet $T_G/^{\circ}C$	Running Time/min
1	93.3	90.5	20
2	93.3	89.5	15
3	93.3	90.0	14
4	93.3	90.2	15
5	93.3	90.6	15
6	93.3	89.8	15
7	93.3	89.9	12

Appendice 7.6

Tabulation - Wind Tunnel Experimental Results

Full Scale deflection = 0.21 - 0.0054 = 0.2046 gm

Time	Scale	Moisture Content (dry basis)	Rate of Moisture Loss	Relative Flux
0	0	0.21	0.0318	1.0
1	16	0.1773	0.0318	1.0
2	32	0.1445	0.0318	1.0
3	45.5	0.1169	0.0250	0.786
4	56.5	0.0944	0.0200	0.629
5	67	0.0729	0.0167	0.525
6	75.5	0.0555	0.0140	0.440
7	82.5	0.0412	0.0120	0.377
8	89.5	0.0269	0.0100	0.314
9	93.5	0.0187	0.0078	0.245
10	97	0.0115	0.0078	0.245
11	100	0.0054		

Appendices 7.7

Tabulation - Evaporative Fluxes (Rotary Dryer Drying Equipment)

RUN	X_o	X_z	f_o	f_z	$f_o(Y_w-Y_{GO})$	$f_z(Y_w-Y_G)$
1	0.105	0.0286	0.695	0.32	0.01682	0.00736
2	0.120	0.0285	0.815	0.32	0.02013	0.00732
3	0.108	0.0361	0.715	0.355	0.01698	0.00797
4	0.118	0.0233	0.795	0.297	0.01924	0.00684
5	0.1	0.0347	0.661	0.350	0.01636	0.00827
6	0.095	0.0266	0.63	0.315	0.01525	0.00711
7	0.1	0.222	0.661	0.29	0.01586	0.00657

Appendice 7.8

Wind-tunnel Experimental Results

Rotameter reading (air flowrate)	=	9.6
Variac settings for heaters	=	140 - 140
Wet-bulb temperature	=	42.5^{o}C
Dry-bulb temperature	=	117^{o}C
Weight of wet particles + "boat"	=	47.56 gm
Weight of dried particles + "boat"	=	43.095 gm
Weight of utterly dried material	=	21.708 gm

Appendices 7.9

Theoretical Drying Rate Profiles

A1 Co-current, adiabatic, drying of slab of infinite extent, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A2 Co-current, adiabatic drying of slab of infinite extent, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

A3 Counter-current, adiabatic, drying of slab of infinite extent, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A4 Counter-current, adiabatic, drying of slab of infinite extent, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

A5 Co-current, isothermal, drying of slab of infinite extent, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A6 Co-current, isothermal, drying of slab of infinite extent, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

A7 Counter-current, isothermal, drying of slab of infinite extent, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A8 Counter-current, isothermal, drying of slab of infinite extent, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

A9 Co-current, adiabatic, drying of spherical particles, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A10 Co-current, adiabatic, drying of spherical particles, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

A11 Counter-current, adiabatic, drying of spherical particle, $\mathcal{N}^o = 10$, $\gamma Bi = 1, 5, 10$

A12 Counter-current, adiabatic, drying of spherical particles, $\mathcal{N}^o = 5$, $\gamma Bi = 1, 5, 10$

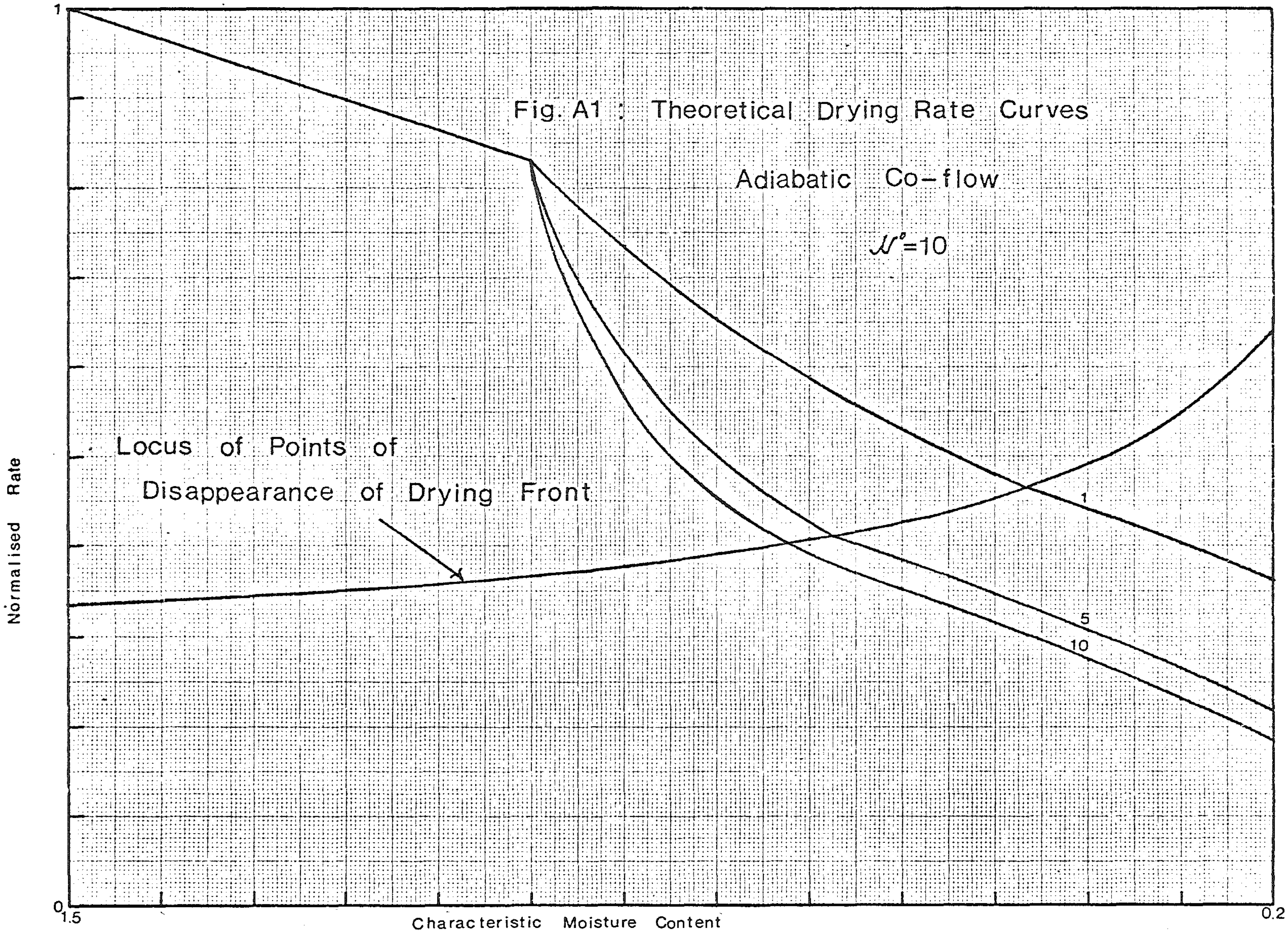
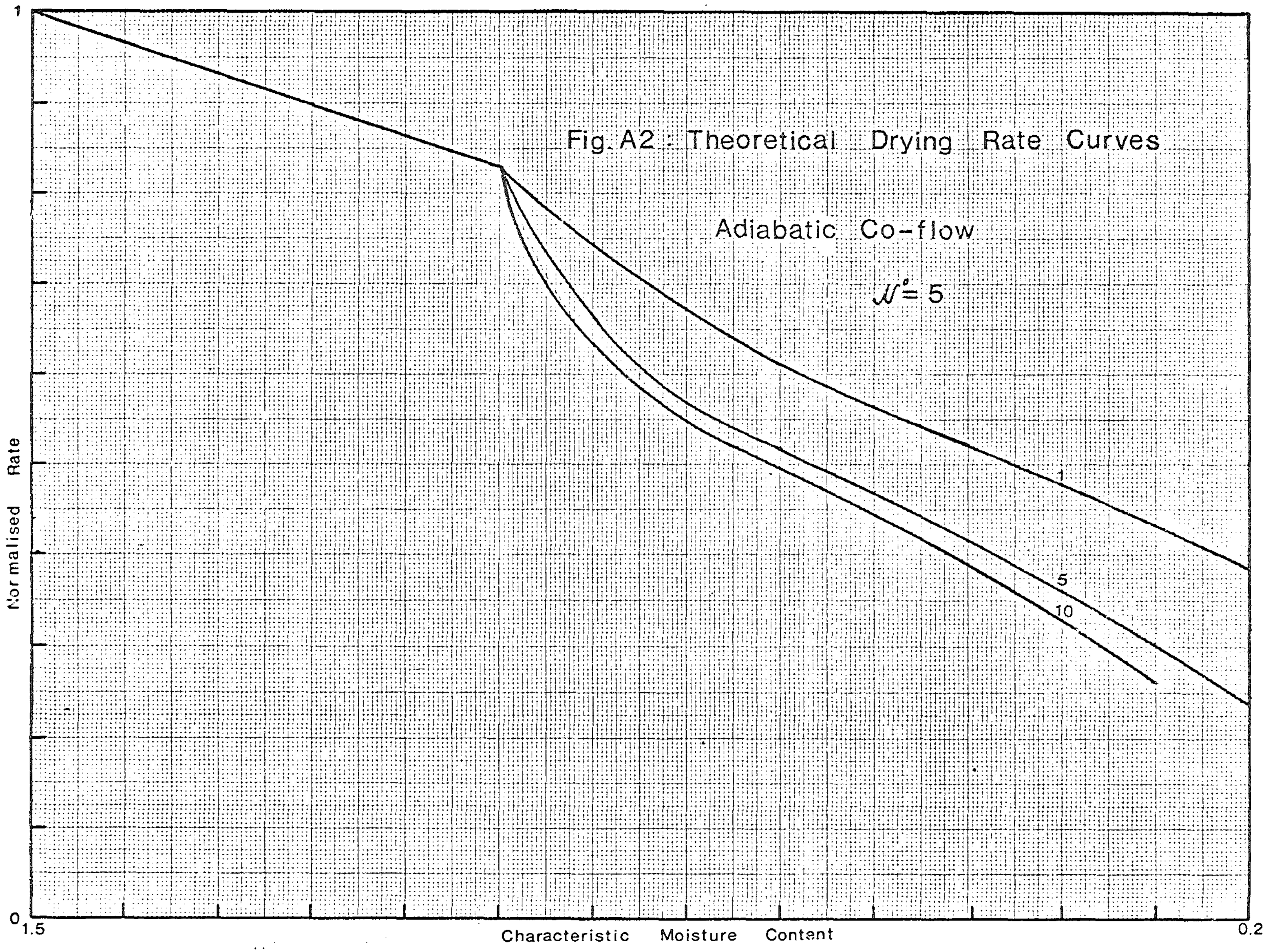
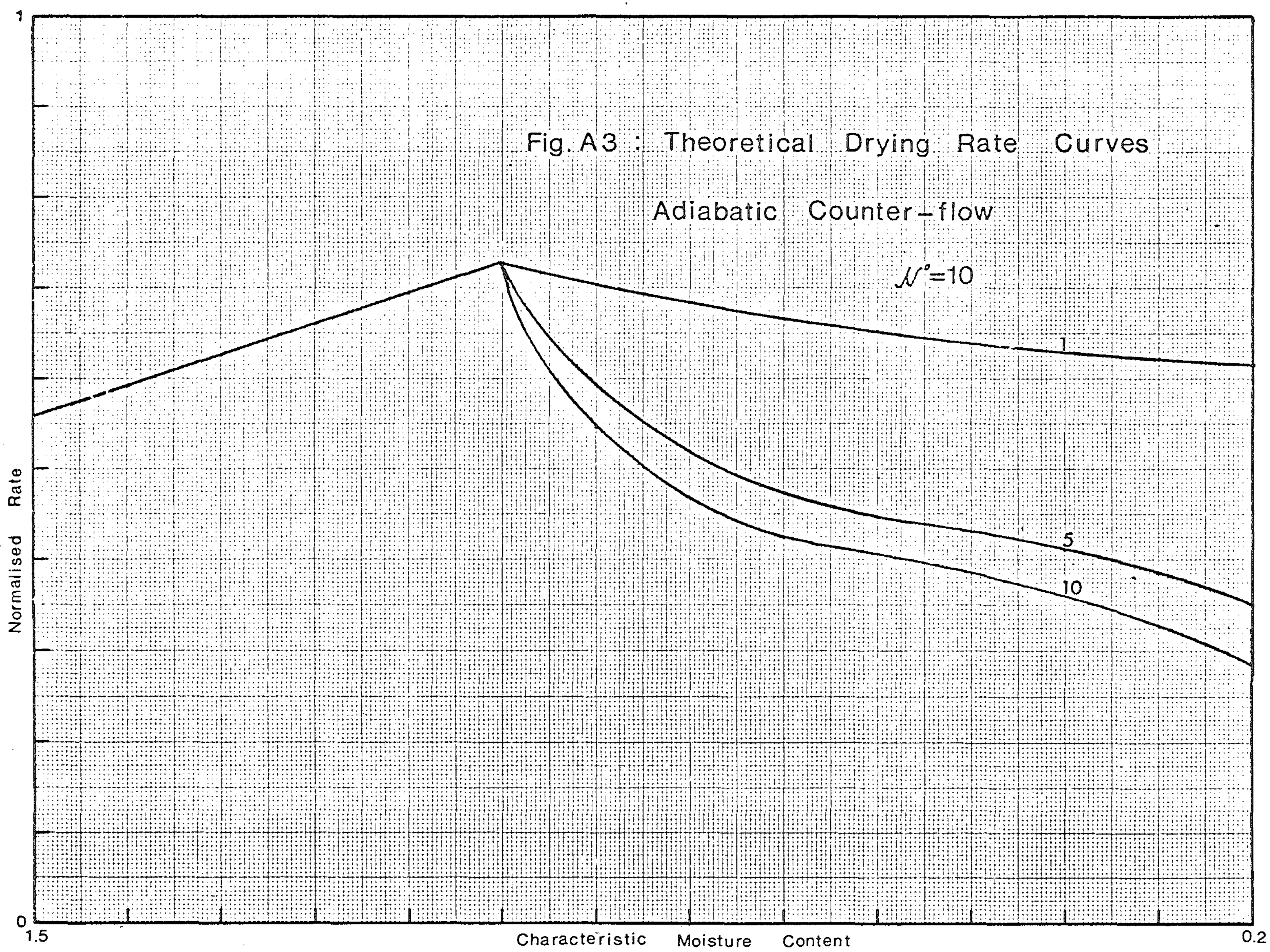


Fig. A1 : Theoretical Drying Rate Curves
Adiabatic Co-flow
$\mathcal{N}^{\circ}=10$
Locus of Points of
Disappearance of Drying Front
1
5
10
1
0
1.5
0.2
Normalised Rate
Characteristic Moisture Content



20 x 26 cm., in mm



20 x 26 cm., in mm

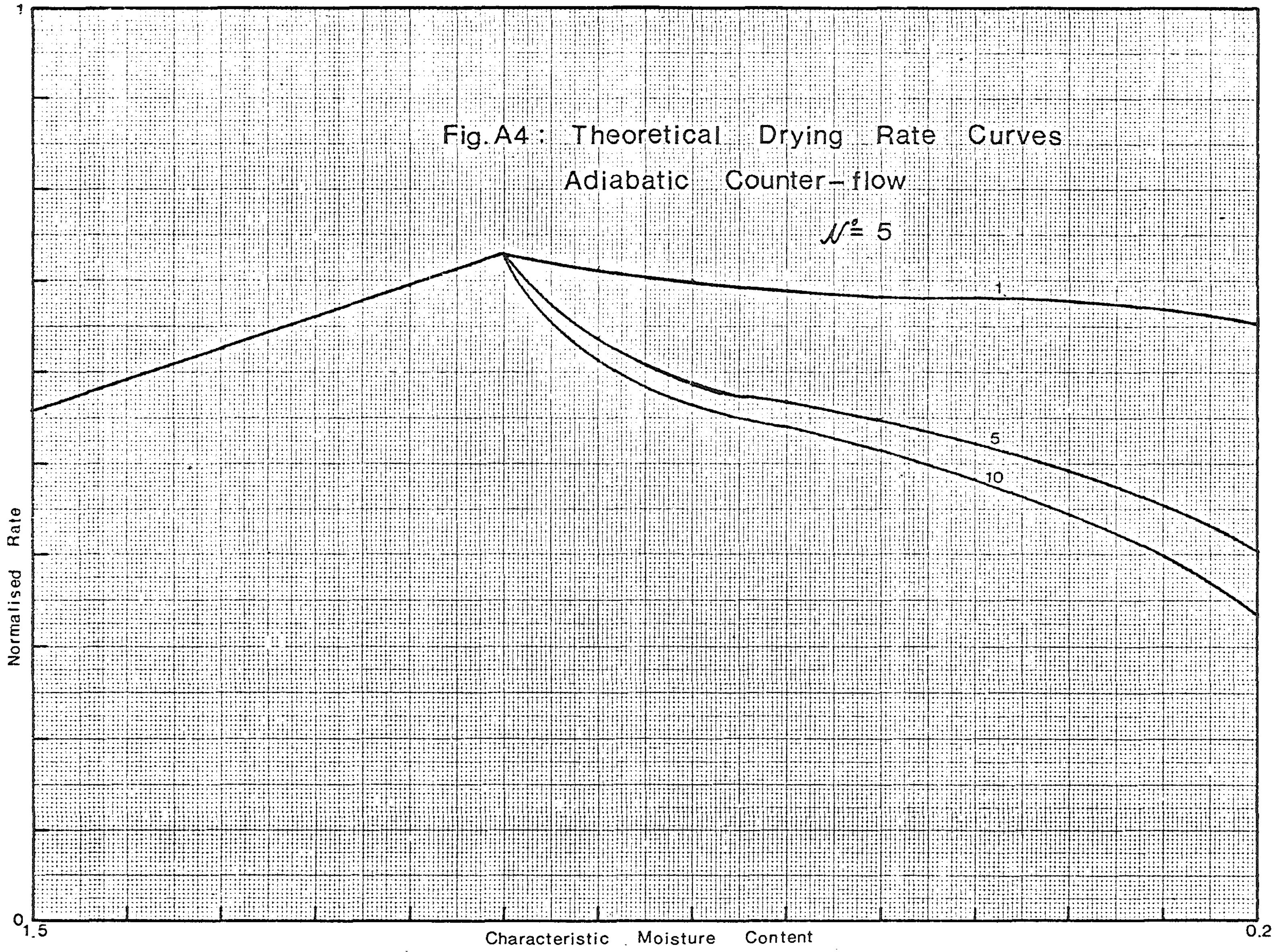
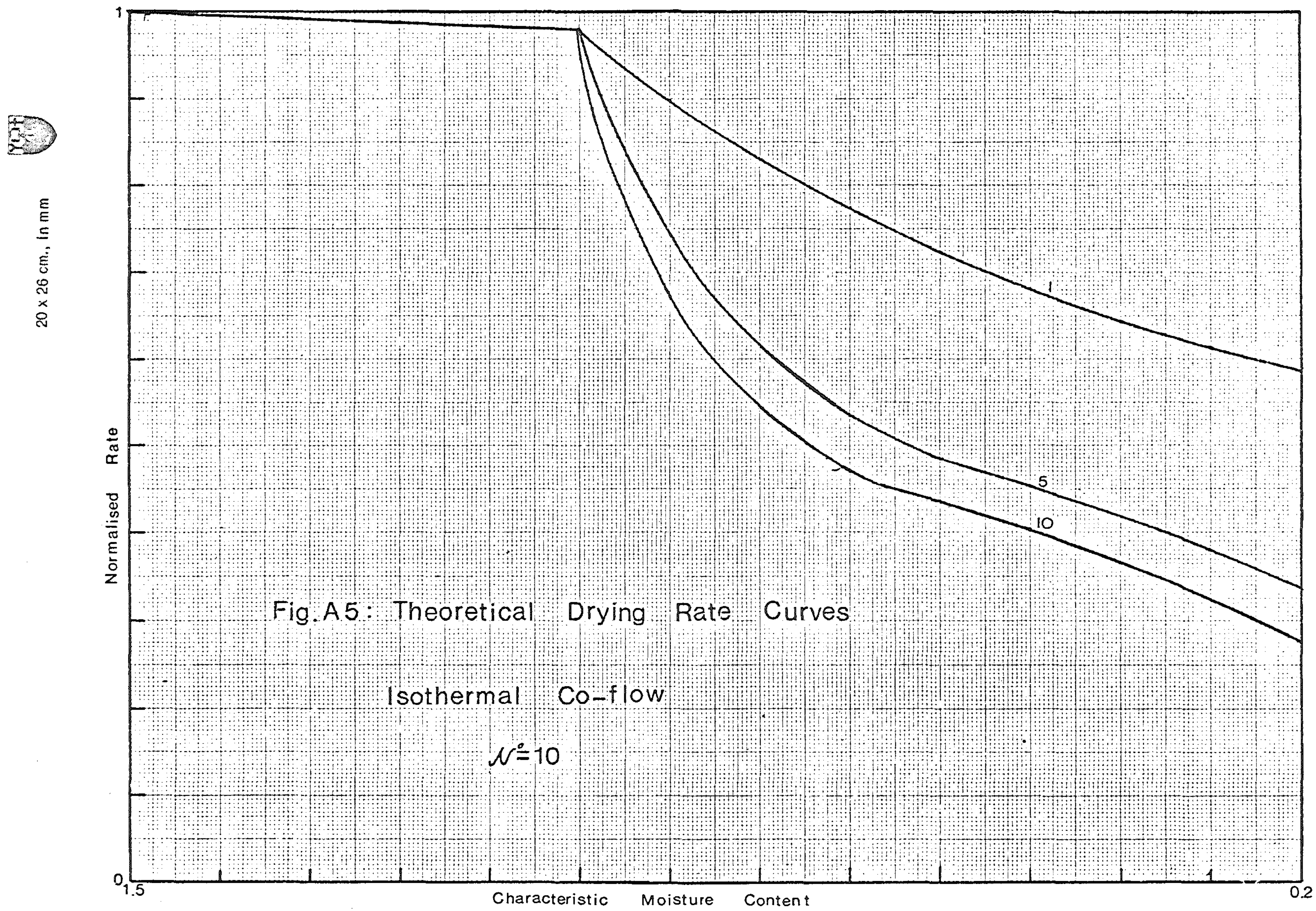


Fig. A4 : Theoretical Drying Rate Curves
Adiabatic Counter-flow
$\mathcal{N}^c = 5$
1
5
10
1
0
1.5
0.2
Normalised Rate
Characteristic Moisture Content

A5



1
0
1.5
0.2
Normalised Rate
Characteristic Moisture Content
1
5
10
Fig. A5: Theoretical Drying Rate Curves
Isothermal Co-flow
$\mathcal{N}^{e} = 10$
20 x 26 cm., In mm

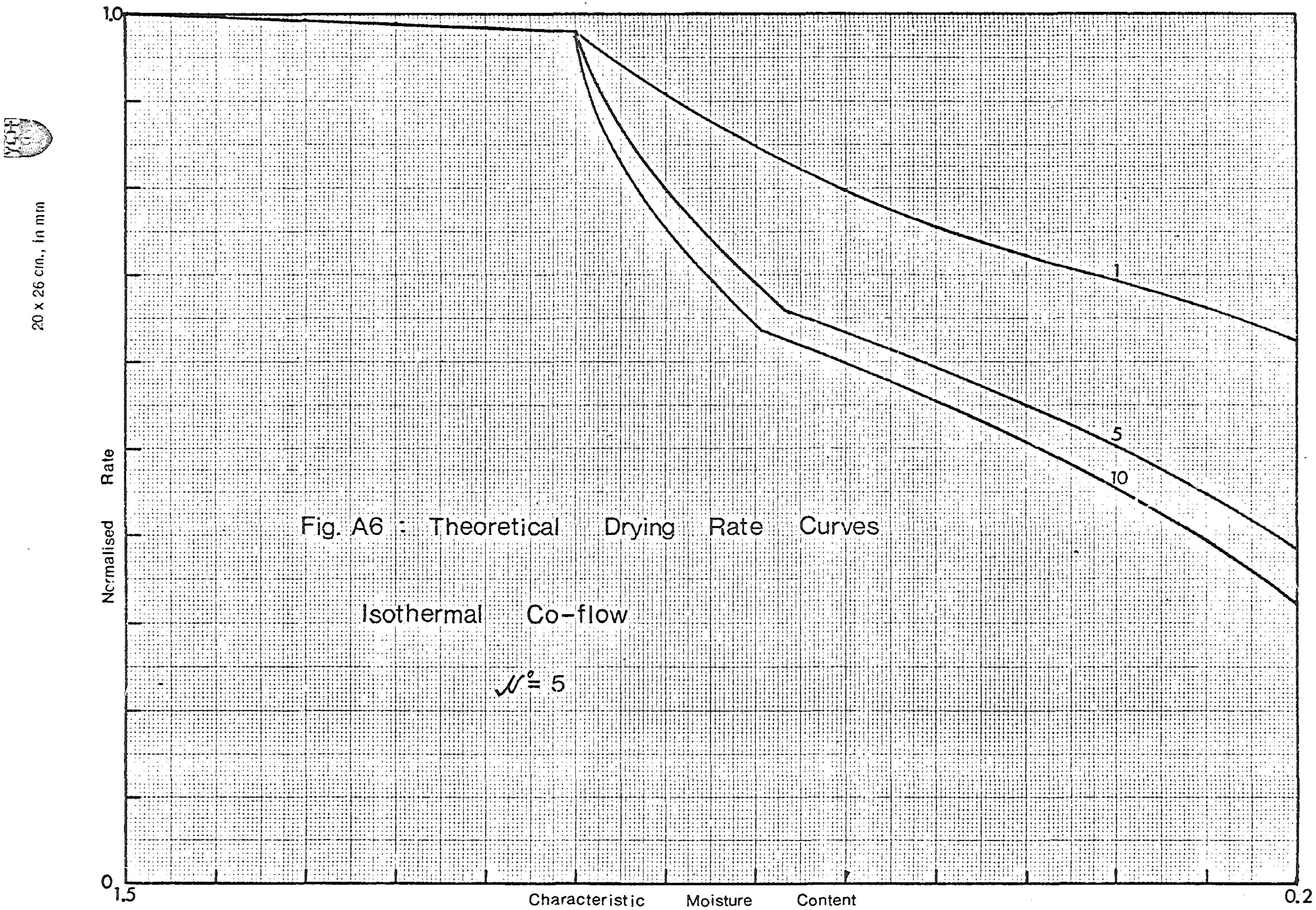


Fig. A6 : Theoretical Drying Rate Curves

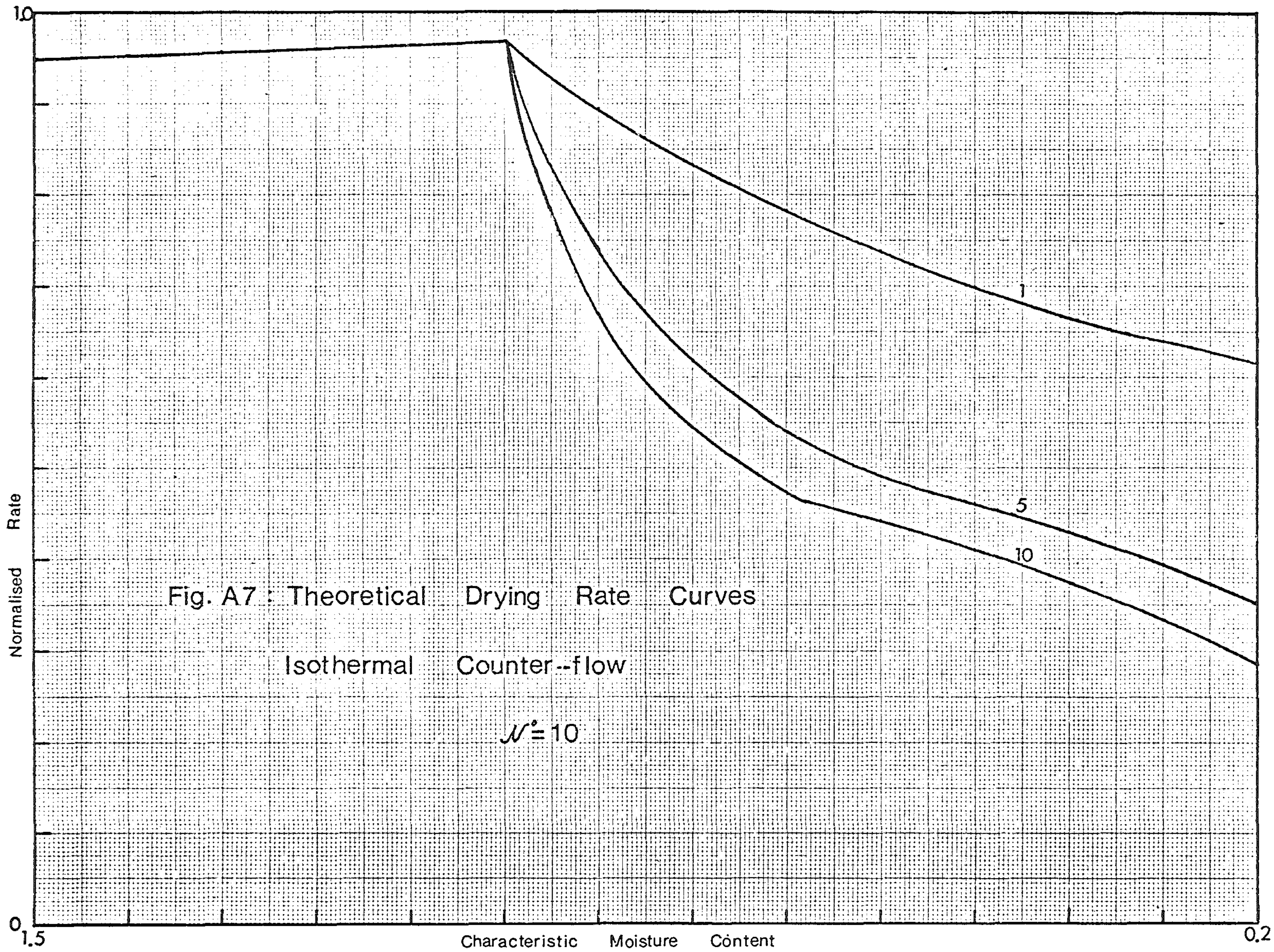
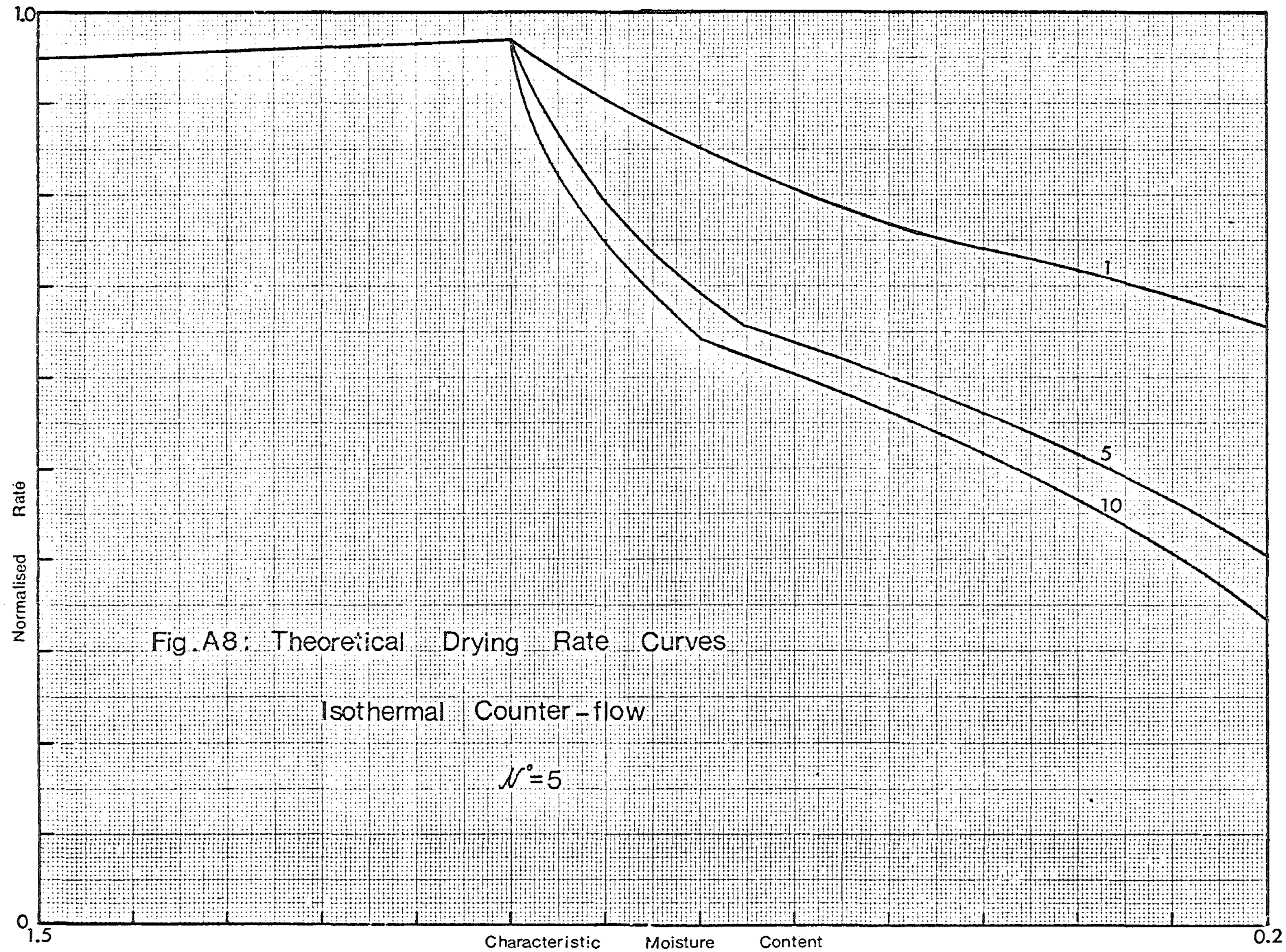


Fig. A7 : Theoretical Drying Rate Curves

Isothermal Counter-flow

$\mathcal{N}^{\circ} = 10$



20 x 26 cm., In mm

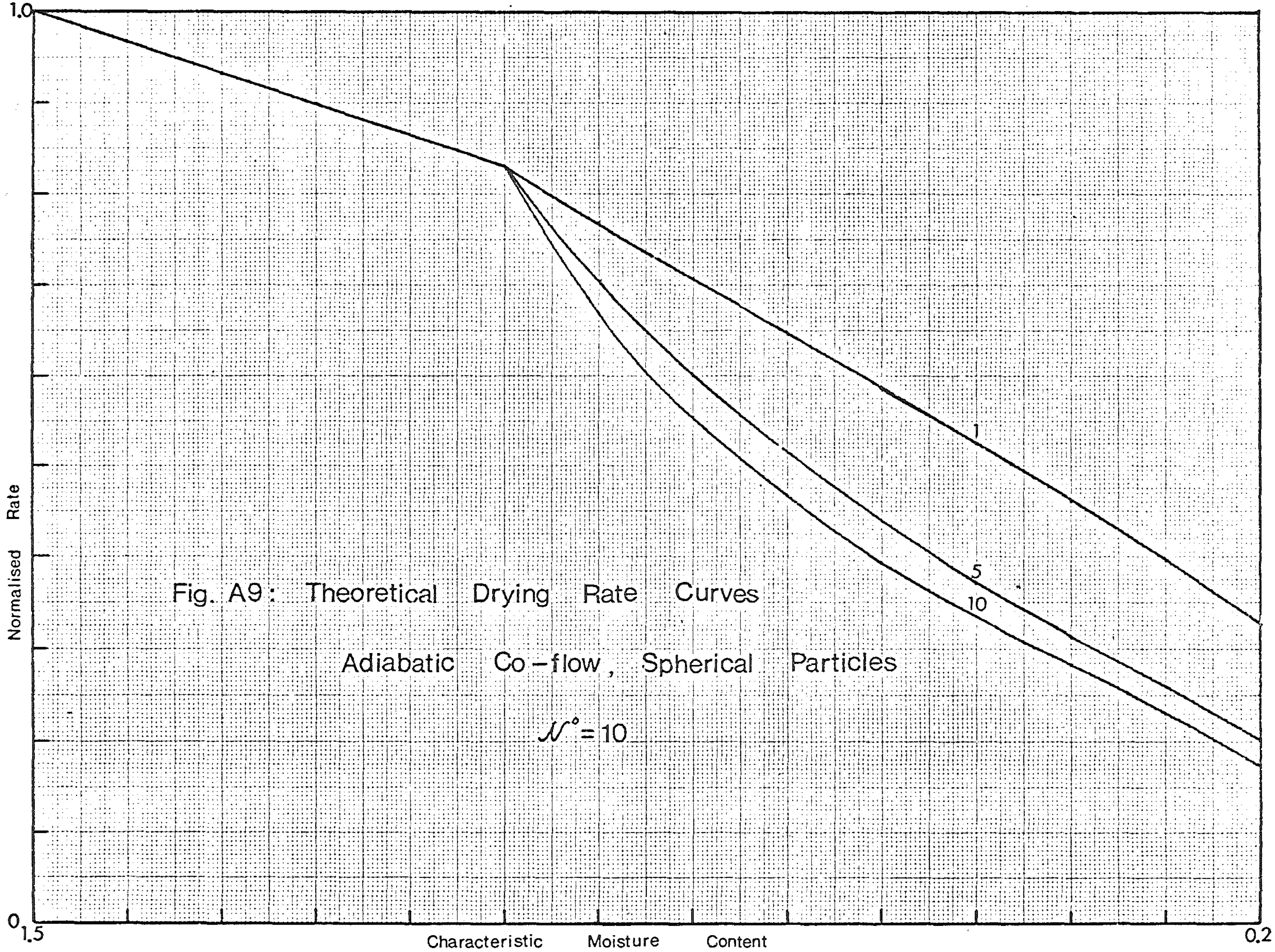


Fig. A9 : Theoretical Drying Rate Curves

Adiabatic Co-flow, Spherical Particles

$\mathcal{N}^{\circ} = 10$

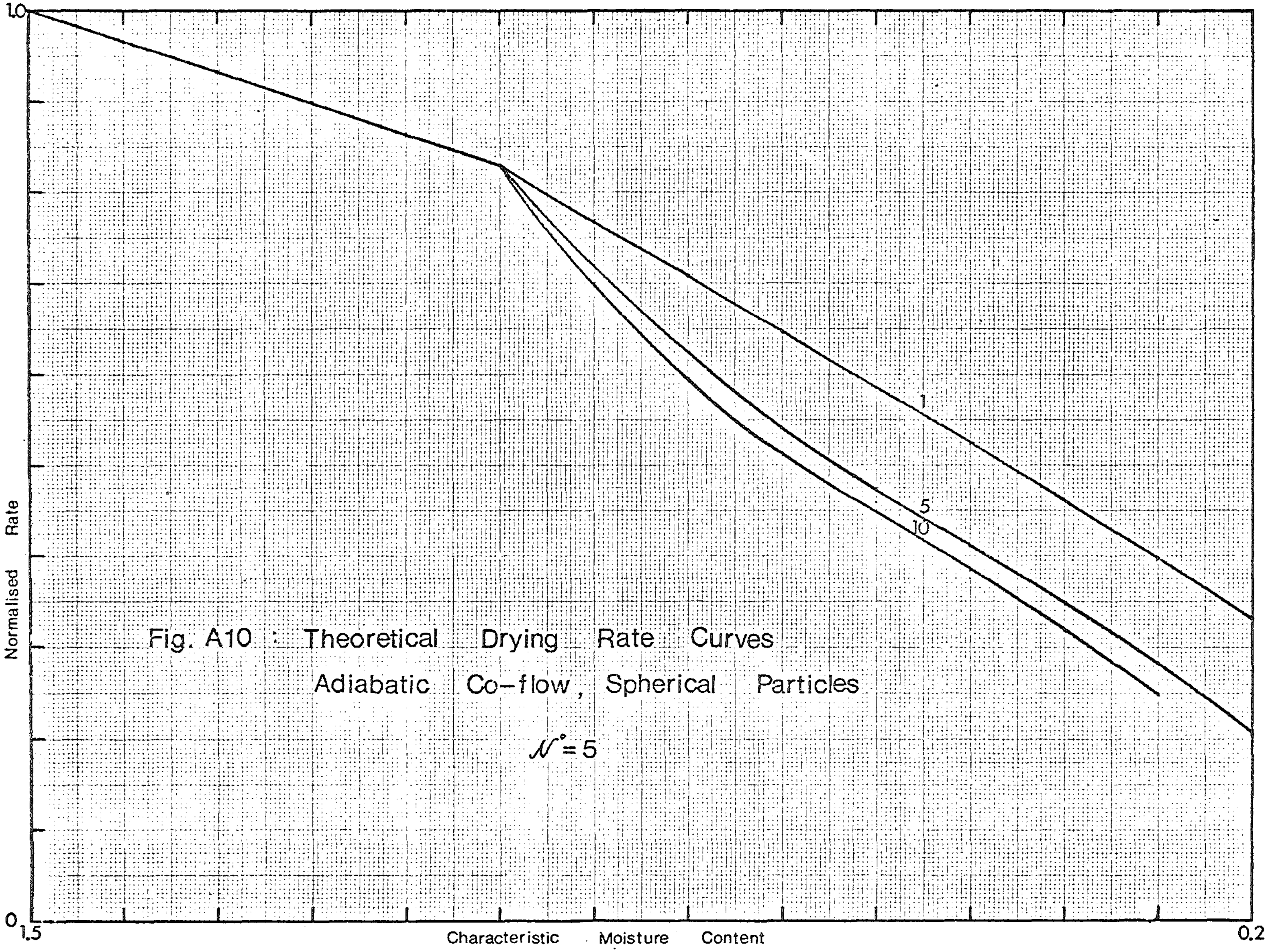
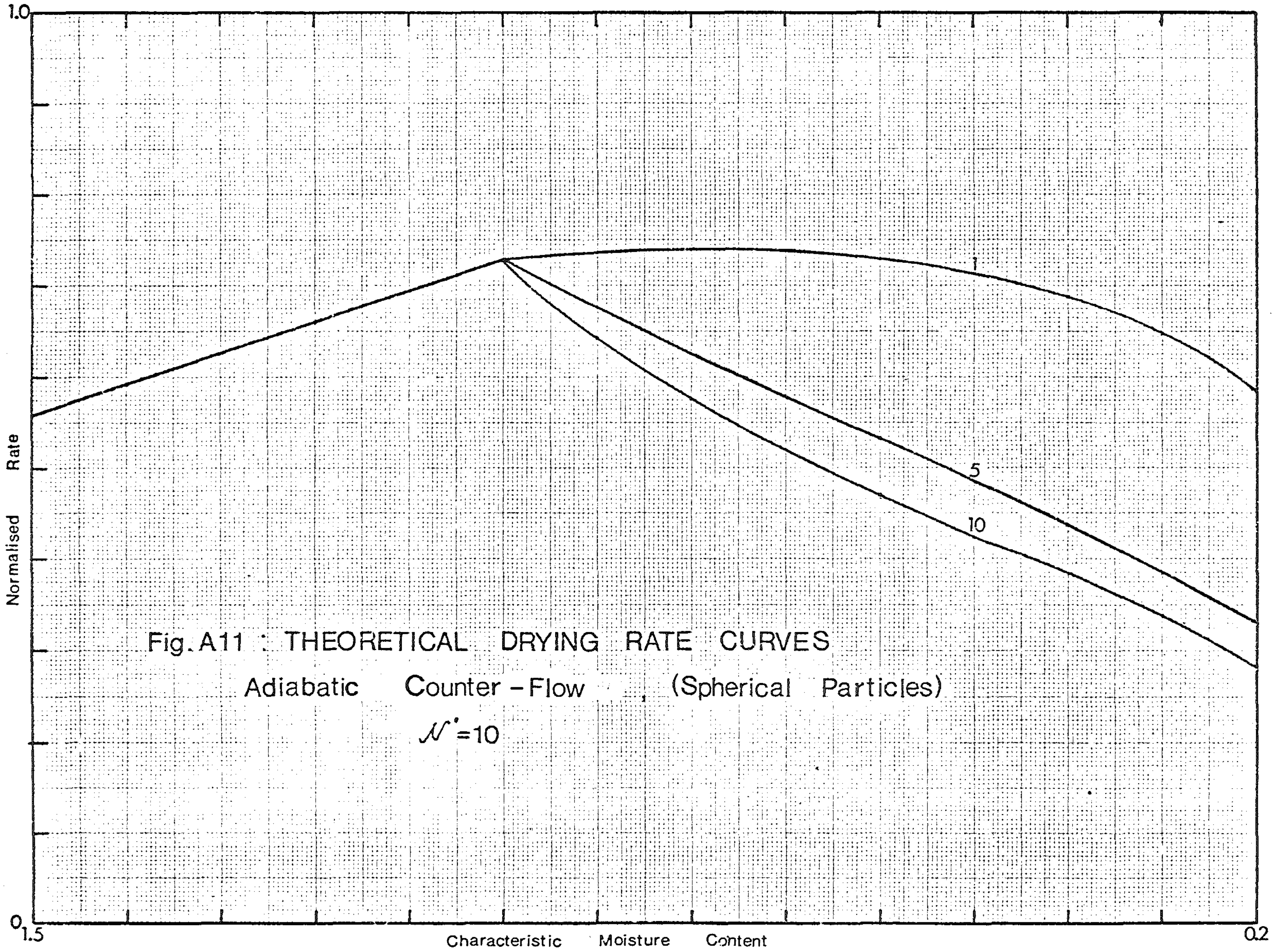
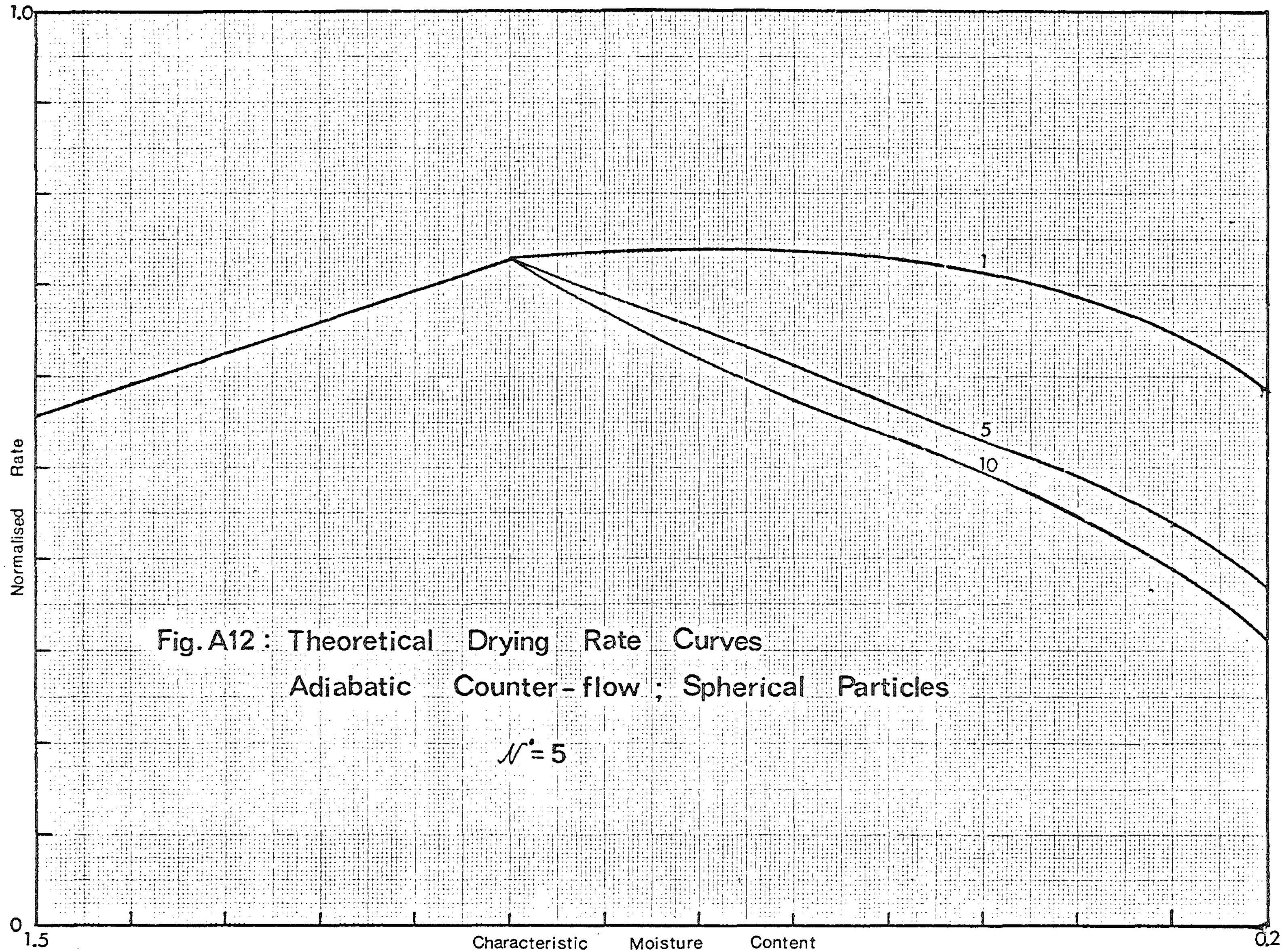


Fig. A10 : Theoretical Drying Rate Curves
Adiabatic Co-flow, Spherical Particles
$\mathcal{N}^{\circ} = 5$

20 x 26 cm., in mm


1.0
0
1.5
0.2
Normalised Rate
Characteristic Moisture Content
1
5
10
Fig. A11 : THEORETICAL DRYING RATE CURVES
Adiabatic Counter - Flow , (Spherical Particles)
$\mathcal{N}^{*}=10$



20 x 26 cm., in mm

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9.0 NOTATION

A_p	area of particle	m^2
b	material thickness	m
Bi	Biot number	-
C	constant	-
C_p	heat capacity of dry gas	$kJ\ kg^{-1}\ K^{-1}$
d	diameter of rotary dryer	m
d_p	diameter of particle	m
D_a	apparent diffusion coefficient for moisture movement through wet material	m^2s^{-1}
D_{ab}	diffusion coefficient of moisture vapour through air	m^2s^{-1}
E	variable (defined in equ. (2.9))	-
f	relative drying flux	-
f_o	relative drying flux at solid inlet	-
f_z	relative drying flux at solid outlet	-
G	specific gas flowrate	$kg\ m^{-2}s^{-1}$
H_v	heat of vaporisation	$kJ\ Kg^{-1}$
h_c	heat transfer coefficient	$W.m^{-2}K$
K_y	mass transfer coefficient for humidity differences	$kg\ m^{-2}s^{-1}$
L	specific solid flowrate	$kg\ m^{-2}s^{-1}$
L	length of dryer	m
M_B	density of air	kg
N_a^o	Evaporation flux (solid inlet)	$kg\ m^{-2}s^{-1}$
N_m	Normalised evaporation flux	-
n	Exponent	-
R	Radius of spherical particle	m
S	Cross sectional area of dryer	m^2
T_G	Dry-bulb temperature of bulk air	^oC

T_{GO}	Dry-bulb temperature of bulk air at solid inlet	^oC
T_W	Wet bulb temperature	^oC
T_a	air temperature	^oC
t_s	surface temperature	$_oC$
U	Variable (equ. 3.16)	-
U	Overall heat transfer coefficient	$N\ m^2k^{-1}$
V	Variable (equ. 3.17)	-
V	Volume of dryer	m^3
V_p	Volume of particle	m^3
W	Variable (equ. 3.18)	-
W	Evaporation rate	kgs^{-1}
X	Moisture content (dry basis)	-
X_{cr}	Critical moisture content (dry basis)	-
X_o	Inlet moisture content (dry basis)	-
X_z	Outlet moisture content (dry basis)	-
X	Equilibrium moisture content (dry basis)	-
Y_g	Humidity of bulk air	-
Y_{GO}	Humidity of bilk air at inlet	-
Y_W	Saturation humidity at wet bulb temperature	-
	Intensity of drying	-
$_o$	Intensity of drying at solid inlet	-
$_{cr}$	Intensity of drying at critical point	-
Φ	Characteristic moisture content	-
γ	Evaporative - resistance coefficient	-
δ	Fractional penetration of drying front	-
ρ_s	Density of solid	$kg\ m^{-3}$
ξ	Fractional depth of recession of evaporative interface	
Δ	Change in	-
μ_d1	Diffusion-resistance coefficient	
β	Dimensionless transport property of material.	